AN ABSTRACT OF THE THESIS OF

Ishtiaq Ahmad Khan Jadoon for the degree of Doctor of Philosophy in Geology presented on May 20, 1991.

Title: Thin-Skinned Tectonics on Continent/Ocean Transitional Crust, Sulaiman Range, Pakistan.

Redacted for Privacy

Abstract approved: ___________________

Dr. Robert D. Lawrence

Surface and subsurface data from the Sulaiman thrust belt show that nearly all the 10 km thick sequence of dominantly platform (>7 km) and molasse strata is detached at the deformation front. These strata thicken tectonically to a minimum of 20 km in the hinterland of the Sulaiman fold belt without significant thrust faults at the surface. The balanced structural cross-section suggests that the tectonic uplift in the Sulaiman fold belt is a result of thin-skinned, passive-roof duplex style of deformation. The duplex sequence of Jurassic and older rocks is separated from the roof sequence by a passive-back thrust in thick Cretaceous shales. The passive-roof sequence remains intact for about 150 km and becomes emergent along a passive-back thrust in the hinterland. The structures are expressed at the surface by fault-related folds in the foreland and out-of-sequence structures (secondary faults and related pop-ups) in the interior. The duplex structure varies from fault-bend folds to anticlinal stacks, and hinterland dipping duplexes. Progressive deformation reveals a series of structural and geometrical features including: (1) broad concentric folding at the fault tip; (2) development of a passive-roof and duplex sequence; (2) forward propagation of the duplex as critical taper is achieved; (4) tear faults and extensional normal faults within the overthrust wedge; and (5) out of sequence (secondary) thrusting. The 349 km long balanced cross-section from the Sulaiman fold belt restores to an original length of 727 km that provides 378 km of shortening in the cover strata of the Indian subcontinent. Minimum estimate of shortening is 328 km. Modelling of the Bouguer gravity profile from the Sulaiman foredeep across the Indian/Afghan collision zone suggests the depth to the Moho at the Sulaiman deformation front is about 36 km. Depth to Moho increases northward with a gentle gradient of 1.1° (20 m/km) for 280 km to the hinterland where the depth to the

Moho is about 42 km. About 150 km north across the Khojak flysch the Moho gradient steepens abruptly to about 7.8° (136 m/km) to attain an average depth of about 57 km in eastern Afghanistan. This suggests that the Sulaiman fold belt is underlain by transitional crust associated with the western passive margin of the Indian subcontinent.

Thin-Skinned Tectonics on Continent/Ocean Transitional Crust, Sulaiman Range, Pakistan

by

Ishtiaq Ahmad Khan Jadoon

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Completed May 20, 1991
Commencement June 1992

APPROVED:

Redacted for Privacy

Dr. Robert D. Lawrence, Associate Professor of Geology

Redacted for Privacy

Dr. Cyrus W. Field, Chairman of department of Geosciences

Redacted for Privacy

Dr. John C. Ringle, Dean of Graduate School

Date thesis is presented May 20, 1991

Presented by Ishtiaq A. K. Jadoon

DEDICATED TO MY PARENTS AND SISTER ANILA JADOON

ACKNOWLEDGEMENT

This work in the Sulaiman fold belt is part of a cooperative project between Oregon State University (OSU) and Hydrocarbon Development Institute of Pakistan (HDIP). Additional data were provided by Amoco, Texaco Overseas, and by Shahid Hassan Khan from the Geological Survey of Pakistan (GSP). Financial support was provided by United States Agency for International Development (USAID) grants to Pakistan Government and by NSF grants INT-86-09914 and EAR-8816962. Northwest Geophysical Associates of Corvallis are acknowledged for donating the GM-SYS program to the Geosciences Department at Oregon State University for gravity modelling on an IBM AT computer.

Thanks are due to Bob Lawrence, Bob Lillie, Bob Yeats, Alan Niem, and Jon Kimerling for critical review of the manuscript. I appreciate enthusiastic guidance from Bob Lawrence, his willingness to share new ideas, and illuminating discussions throughout the completion of this project. My foremost thanks to Bob Lillie for his dynamic, and critical guidance. He inspired me to work independently and confidently. It would not have been possible to complete this work effectively and timely without his constant enthusiasm and support. Reviews of section 2 by J. Warburton, and Chris Izatt and of Bouguer gravity interpretations in section 4 by Kees Dejong, and Leonardo Seeber are gratefully acknowledged.

I acknowledge the company and thought provoking disscussions with Dan Davis, Ghazanfar Abbas, and others during our first field trip to the Sulaiman in fall 1988. Special thanks are due to Hilal Raza, Riaz Ahmad, Manshoor Ali, Jalil Ahmad, and Amjid Cheema from HDIP and Mohamad Ilyas (Assistant Commissioner, Kohlu) for their cooperation, time, and sincere effort in assembling the data and logistic problems.

I take this moment to acknowledge Azam Ali, Aslam Awan, Mirza Baig, Gary Huftile, Mansoor Humayon, Khurshid Akbar, Mazhar Qayyum, Qadar Abbasi, Vera Langer, and many others who have been of help in different ways during the preparation of this thesis. Special thanks to my wife, Faria Jadoon for providing me a good working environment.

TABLE OF CONTENTS

SECTION 4

LIST OF FIGURES

Thin-skinned tectonics on continent/ocean transitional crust, Sulaiman Range, Pakistan

SECTION 1

GENERAL INTRODUCTION

The Himalayan collision zone extends over 5000 km in Burma, Nepal, India, and Pakistan (Gansser, 1981). The Himalayas have been actively growing since 55 Ma (Powell, 1979) due to the collision between Indian and Eurasian plates. In the Main Himalayas, continent/continent collision is in progress due to advanced stage of convergence (Lefort, 1975). This extensive mountain system manifests variable tectonic and morphological features in the main Himalaya to broad oroclinal structures at its flanks (Seeber and Armbruster, 1979; Sarwar and Dejong, 1979; Tahirkheli and Jan, 1979; Gansser, 1981; Yeats and Lawrence, 1984; Farah et al, 1984; Molnar, 1984; Mattauer, 1986; Searle, 1986; Searle et al, 1987; Baig, 1990). The narrow ~30 km Himalayan foreland fold-and-thrust belt in India broadens to more than 100 km along a series of lobes in Pakistan (Sarwar and Dejong, 1979; Seeber, 1981; Lillie et al, 1987; Jaume and Lillie, 1988). The Sulaiman fold-and-thrust belt located along the western edge of the Indian subcontinent is the broadest (>300 km) of these lobes.

The structure and tectonics of the Sulaiman fold-and-thrust belt, which has gentle (<1°) topography and a broad width (>300 km), are poorly understood. Major work in the Sulaiman fold belt was done in the early 1960's by Canadians under a cooperative project with the Government of Pakistan (Hunting Survey Corporation, 1961). They produced geological maps on a scale of 1:253,440 based mainly on air photo interpretation. Abdul-Gawad (1971) and Rowlands (1978) recognized some neotectonics features. Many papers in the Geodynamics of Pakistan (Farah and DeJong, eds., 1979) provide a good overview of the regional tectonics and seismicity in the Sulaiman fold belt. Recently, alternate ideas ranging from imbricate structures (Bannert et al, 1979) to passive-roof duplex geometries (Banks and Warburton, 1986; Humayon et al, 1991) have been presented for the structural evolution of the Sulaiman fold belt. S-wave studies of earthquakes (Chun, 1986) and Bouguer gravity modeling (Khurshid, 1991; Lillie, 1991) from the Sulaiman fold belt infer an extended transitional/oceanic crust under the Sulaiman fold belt. This contrasts with the crustal structure of the main Himalaya where crust of double the normal continental thickness is suggested based on P-wave studies of earthquakes (Gupta and Narain, 1967; Chun and Yoshii, 1977) and Bouguer gravity modeling (Duroy et al, 1989). In this thesis, all available surface and subsurface data are used to construct a balanced structural and crustal section to understand the structure and evolution of the active Sulaiman fold belt. Structures in this work are analysed on a macroscopic scale. However, observation of structures on all scales were vital to interpret the primary macroscopic structures. Manuscripts in section 2 and 3 contain more specific background for section 4. The structures along the balanced cross-section were field checked during two field seasons in the fall of 1988 and winter of 1989.

Seismic reflection, surface geology, Landsat and existing gravity data from the Sulaiman fold belt were available to Oregon State University through a joint project with Oil and Gas Development Corporation of Pakistan (OGDC), Hydrocarbon Development Institute of Pakistan (HDIP), and Geological Survey of Pakistan. Additional seismic reflection data were provided by Amoco and Texaco overseas.

Balanced and retrodeformed geological cross-section from the frontal Sulaiman Lobe, Pakistan: Duplex development in thick strata along the western margin of the Indian Plate

SECTION 2

ABSTRACT

A balanced cross-section has been constructed integrating seismic reflection profiles, drillhole, surface geology, and Landsat data across the tectonically active frontal Sulaiman fold belt in the western Himalayas. Restoration of the section provides information regarding the chronology of structures, structural style, sequence of thrusting, and the amount of shortening. General structural form evidenced by gentle topography and a broad fold belt is similar to that of other mountain belts underlain by weak detachments. A sequence of about 10 km of dominantly platform (>7 km) and molasse strata thickens tectonically to about 15 km, 129 km north of the southwards verging deformation front. Nearly all of the 10 km thick stratigraphic sequence has been detached at the deformation front. Structural style is that of a hinterland-dipping duplex separated from the roof sequence by a passive-roofthrust in thick Cretaceous shale. This structure is expressed at the surface by fault-related folds. Toward the northerly hinterland, progressively older rocks are present at the surface in the hinge zones of the anticlines. They have been uplifted by duplexing several kilometers higher than their regional stratigraphic level. The passive-roof thrust has not been cross-cut by backthrusts, and it is present over a distance of 60 km along the line of section. Progressive deformation reveals a series of structural and geometrical features including: (1) broad concentric folding at the fault tip; (2) development of a passive roof and duplex sequence by forward propagation of floor and roof thrusts; (3) forward propagation of the duplex as critical taper is achieved; and (4) tear faults and extensional normal faults within the overthrust wedge. A retrodeformed cross-section shows that about 76 km of orogenic contraction in the cover sequence has occurred across the frontal 129 km of the Sulaiman fold belt.

INTRODUCTION

The Himalayan mountain system represents an active continent-continent collision zone extending westward from Burma through northern India and Nepal into Pakistan (Gansser, 1981). The broad Sulaiman fold belt is developed by transpression as a result of the left-lateral strike-slip motion along the Chaman fault zone and southward thrusting along the western boundary of the Indian subcontinent (Fig. 2.1 and 2.2; Sarwar and Dejong, 1979; Lawrence et al, 1981; Farah et al, 1984; Quittmeyer et al, 1984). The frontal part of the Sulaiman fold belt is seismically active (Quittmeyer et al, 1979, 1984); however, the stratigraphy is not disrupted by any thrust faults that break the surface (Fig. 2.3). The style of deformation from the western Sulaiman fold-and-thrust belt is reported to be that of hinterland-dipping duplexes developed in a piggyback fashion (Banks and Warburton, 1986). Southward migration of the deformation front sheds erosion products into the active Sulaiman foredeep, where 7 km of molasse strata are currently present in the Sibi molasse basin (Banks, and Warburton, 1986).

Recent studies constrained by seismic reflection and borehole data in the North American Cordillera, Appalachians, Alps, Himalayas, and Taiwan have provided insight into the mechanism of deformation and geometry of structures in the frontal part of collision zones (Rich, 1934; Dahlstrom, 1969a, 1970; Suppe, 1980, 1983; Laubscher, 1981; Acharyya and Ray, 1982; Bachman et al, 1982; Jones, 1982; Davis et al, 1983; Davis and Engelder, 1985; Banks and Warburton, 1986; Boyer, 1986; Mitra, 1986; Lillie et al, 1987; Jaume and Lillie, 1988; McDougall and Hussain, 1991; Izatt, 1990). Studies of active mountain belts (i.e., Himalaya and Taiwan) are important because they provide constraints on collisional processes that are unavailable in ancient mountain belts. In this study, seismic reflection and well data, available from the frontal part of the active Sulaiman fold belt are integrated with surface geology and Landsat data (Fig. 2.3 and 2.4) in order to: 1) determine the thickness and nature of the overthrust wedge; 2) analyse the structural style and nature of deformation; 3) study progressive deformation and its effects on basin geometry; and 4) estimate the amount of compressional shortening in the cover of Phanerozoic strata.

TECTONIC SETTING AND STRATIGRAPHY

The Himalayan mountain belt changes trend from northwest-southeast in India to northeast-southwest in Pakistan (Fig. 2.1). Typical of the foreland part of the northwestern Himalaya in Pakistan are two broad lobate features: Salt Range/Potwar Plateau and the Sulaiman fold belt. Their lobate geometry is interpreted to be the result of rapid southward translation along a weak decollement of the tear fault bounded thrust sheets (Sarwar and Dejong, 1979; Seeber et al, 1981). This is similar to the foreland translation of the Pine Mountain thrust block of the Central Appalachians (Rich, 1934; Harris and Milici, 1977) and the Jura Mountains of Europe (Laubscher, 1981). Deformation is progressively younger toward the foreland, as constrained by magnetic stratigraphy (Johnson et al, 1982; Raynolds and Johnson, 1985), active folds and neotectonic activity in parts of the Salt Range/Potwar Plateau (Yeats et al, 1984; Yeats and Lillie, 1991). In the Sulaiman fold belt, progressive deformation is evidenced by structural style (Hunting Survey Corporation, 1961; Kazmi and Rana, 1982), a prominent topographic front, and seismicity under the frontal folds (Quittmeyer et al, 1979, 1984).

Unlike the Salt Range/Potwar Plateau that is associated with the main zone of Himalayan convergence, the Sulaiman fold belt is located along a zone of transpression in the northwestern part of the Indian subcontinent (Fig. 2.1). The broad Sulaiman fold belt is bounded to the west and north by the left-lateral strike-slip Chaman fault zone (Fig. 2.2). The foredeep basin to the east and south of the active Sulaiman Lobe is formed mainly as a result of tectonic compression between the Indian plate and the Afghan block (Fig. 2.2). The initial event of collision is manifested by the emplacement of the Muslimbagh ophiolite between Late Cretaceous and Early Eocene times (Allemann, 1979). An unconformity between Cretaceous and Paleocene rocks in the Attock Cherat Ranges north of the Potwar Plateau (Yeats and Hussain, 1987) extends all the way to the Loralai valley of the Sulaiman Range (Hunting Survey Corporation, 1961). Renewed southward thrusting since late Oligocene-early Miocene constantly reworked the molasse strata migrating the Indus basin farther east and south (Banks and Warburton, 1986; Waheed et al, 1988). This is similar to the southward migration of the active foredeep basins of the Ganges plain in India and the Jhelum plain in Pakistan (Acharyya and Ray, 1982; Raiverman et al, 1983; Johnson et al, 1985; Raynolds and Johnson, 1985).

The main structural elements in the Sulaiman fold belt are east-west trending arcuate folds and faults which rotate rapidly to a north-south direction along the margin of the active fold belt (Fig. 2.2). Imbricate faults are visible at the surface only in the north (Hunting Survey Corporation, 1961; Kazmi and Rana, 1982). They gradually disappear

Figure 2.1. Tectonic features along the western edge of the Indian subcontinent. Area of fig. 2.2 shown by rectangle. JB = Jacobabad high; MK = Mari/Khandkot/Khandkot high; TFZ = Talhar fault zone; SG = Sargodha high.

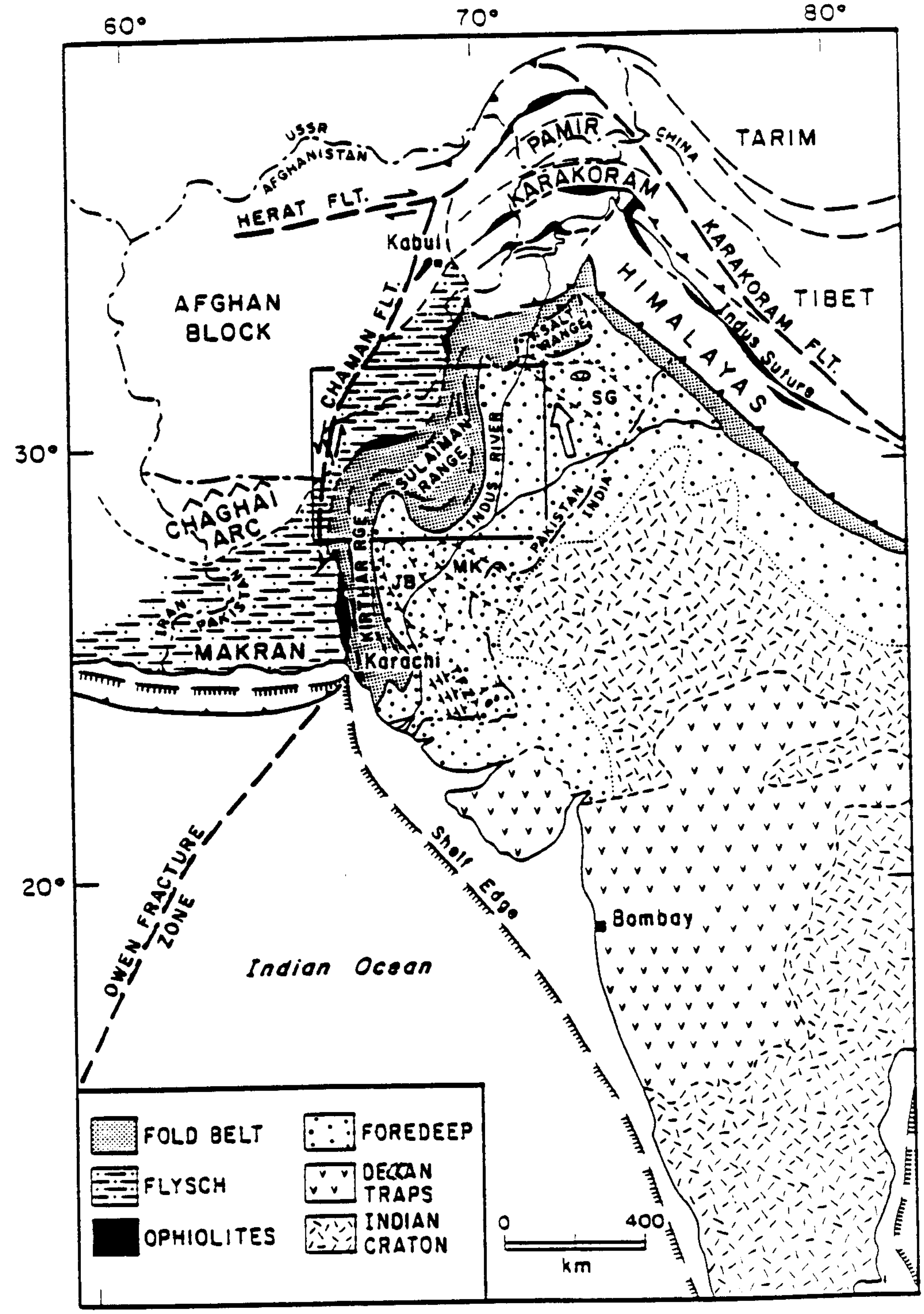

60°
70°
80°
30°
20°
USSR
AFGHANISTAN
HERAT FLT.
PAMIR
CHINA
TARIM
KARAKORAM
Kabul
AFGHAN BLOCK
CHAMAN FLT.
HIMALAYAS
KARAKORAM FLT.
Indus Suture
TIBET
SALT RANGE
SG
SULAIMAN RANGE
INDUS RIVER
CHAGHAI ARC
KIRTHAR RGE
PAKISTAN INDIA
JB
MK
IRAN PAKISTAN
MAKRAN
Karachi
OWEN FRACTURE ZONE
Shelf Edge
Bombay
Indian Ocean
FOLD BELT
FLYSCH
OPHIOLITES
FOREDEEP
DECCAN TRAPS
INDIAN CRATON
0
400
km

Figure 2.1

Figure 2.2. Generalized tectonic map of the Sulaiman fold belt in Pakistan (modified from Kazmi and Rana, 1982). Area of investigation is shown by rectangle (Fig. 2.3). Line AA´ is part of this study, while line BB´ is constructed by Humayun et al, (1990). Cross-sections CC´ and DD´ are shown in fig. 2.5 (after Banks and Warburton, 1986). Line EE´ locates a Bouguer gravity profile (Khurshid, 1991).

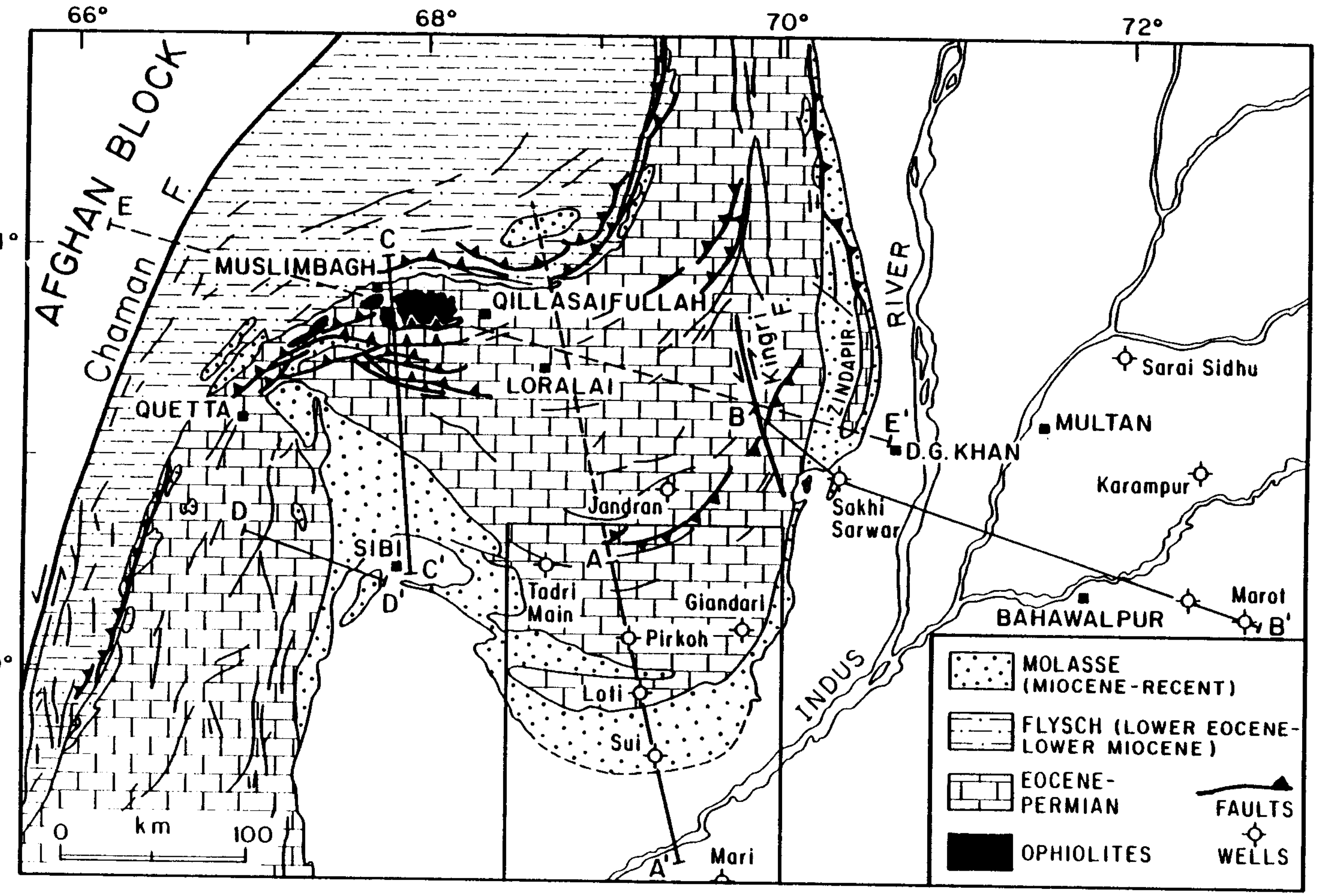
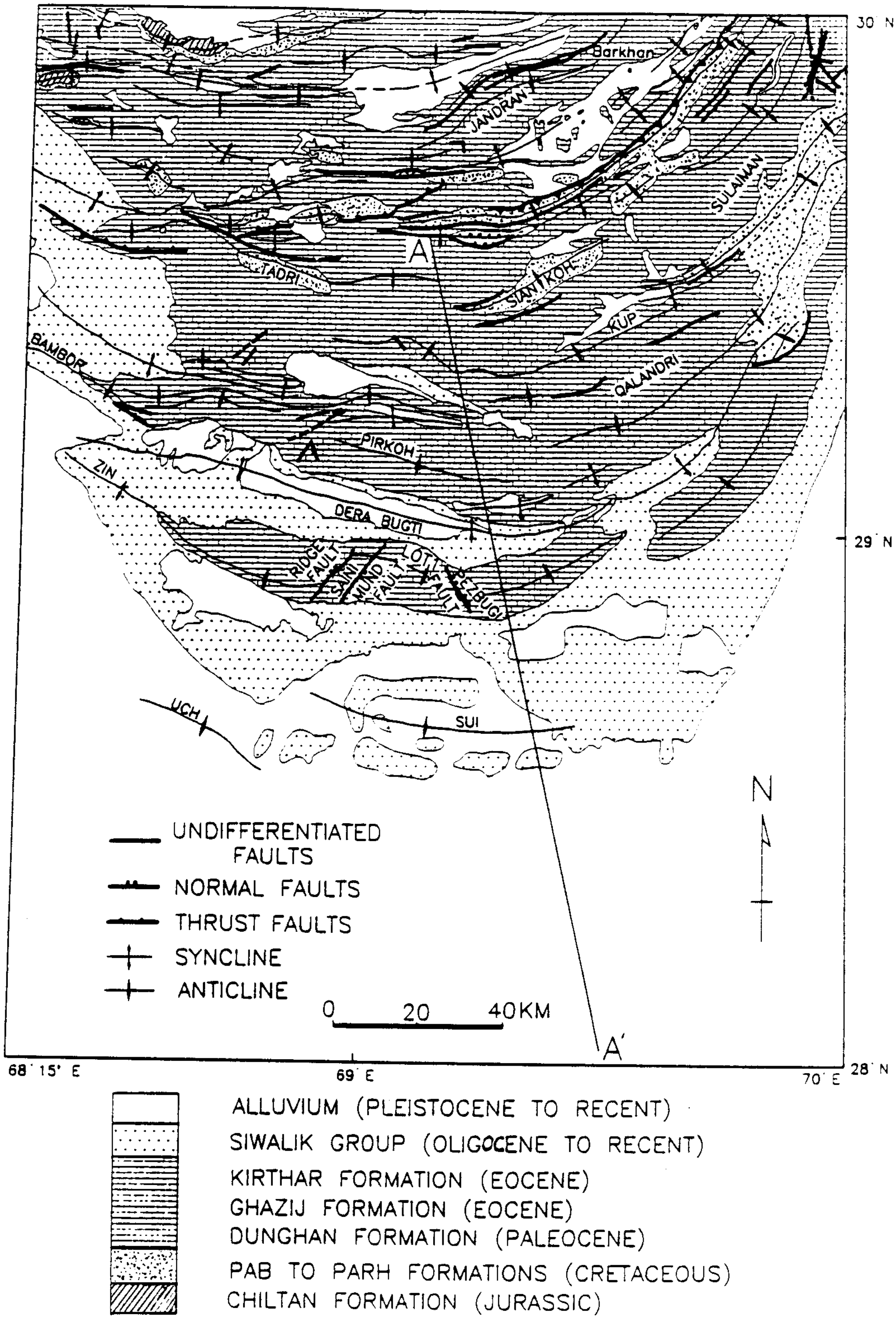

66°
68°
70°
72°
31°
29°
AFGHAN BLOCK
Chaman F.
E
C
MUSLIMBAGH
QILLASAIFULLAH
LORALAI
QUETTA
Kingri F.
ZINDAPIR
RIVER
B
E'
D.G. KHAN
MULTAN
Sarai Sidhu
Karampur
Jandran
Sakhi Sarwar
D
SIBI
C'
D'
A
Tadri Main
Giandari
Pirkoh
Loti
Sui
INDUS
BAHAWALPUR
Marot
B'
A'
Mari
0 km 100
MOLASSE (MIOCENE-RECENT)
FLYSCH (LOWER EOCENE-LOWER MIOCENE)
EOCENE-PERMIAN
FAULTS
OPHIOLITES
WELLS

Figure 2.2

Figure 2.3. Generalized geological map of the southern Sulaiman lobe. Mapping is compiled from the unpublished maps of the Oil and Gas Development Corporation (OGDC), the Geological Survey of Pakistan (GSP), the Hunting Survey Corporation (1961), and from Landsat images (1:125,000) supplied by Earth Satellite Corporation. Available seismic reflection data is shown in fig. 2.4. Deformed and retrodeformed section (AA′) is shown in Fig. 2.9.



30° N
29° N
28° N
68° 15' E
69° E
70° E
Barkhan
JANDRAN
SULAIMAN
TADRI
SIAN KOH
KUP
QALANDRI
BAMBOR
PIRKOH
ZIN
DERA BUGTI
RIDGE FAULT
SAINI
MUND FAULT
LOTI FAULT
PEZBUGI
UCH
SUI
A
A'
N
UNDIFFERENTIATED FAULTS
NORMAL FAULTS
THRUST FAULTS
SYNCLINE
ANTICLINE
0 20 40KM
ALLUVIUM (PLEISTOCENE TO RECENT)
SIWALIK GROUP (OLIGOCENE TO RECENT)
KIRTHAR FORMATION (EOCENE)
GHAZIJ FORMATION (EOCENE)
DUNGHAN FORMATION (PALEOCENE)
PAB TO PARH FORMATIONS (CRETACEOUS)
CHILTAN FORMATION (JURASSIC)

Figure 2.3

toward the frontal part of the fold belt in the subsurface. Tear faults, such as the Kingri fault, manifest neotectonic activity by the offset of fold axes, faults, uplifted and tilted gravel beds, and major bends along the course of the streams (Abdul-Gawad, 1971; Rowlands, 1978). Banks and Warburton (1986) constructed a balanced structural cross-section along the western part of the Sulaiman fold belt (Fig. 2.5). This suggests a line-length shortening of about 126 km along hinterland-dipping duplexes beneath a passive-roof backthrust.

Rocks from the Sulaiman fold belt can be divided into three main groups to emphasize their tectonic significance (Fig. 2.2). From south to north these units are: (1) late Oligocene to Recent molasse deposits; (2) Eocene to Permian, shallow-marine shelf to deep marine rocks (Kazmi and Rana, 1982)); and (3) late Eocene to early Oligocene Khojak Flysch (Lawrence and Khan, 1991a). The Muslimbagh ophiolites in the Zhob valley represent pieces of oceanic crust thrust over Maestrichtian shelf strata (Abbas and Ahmad, 1979). Figure 2.6 provides a summary of the stratigraphy of the Sulaiman fold belt at the deformation front based on surface geology, well data, and seismic reflection profiles. The exposed Eocene to Permian rocks from the Sulaiman fold belt are similar to those of the Salt Range, except that the 7-km-thick carbonate-dominated sequence is much thicker than that of the Salt Range. The Sulaiman fold belt with such a thick, sedimentary section yet with relatively high Bouguer gravity anomalies is interpreted to overlie an extended crust (Lillie et al, 1989; Jadoon et al, 1990; Khurshid, 1991).

Seismicity from the frontal part of the Sulaiman fold belt (Quittmeyer et al, 1984), along with multiple unconformities in the Siwalik molasse (Iqbal and Shah, 1980; Banks and Warburton, 1986) illustrate the ongoing deformation that is taken up by broad folds along the southern Sulaiman front.

GENERAL OBSERVATIONS FROM INTEGRATION OF SURFACE AND SUBSURFACE DATA

Seismic reflection profiles from the frontal part of the Sulaiman fold belt and the adjacent foredeep in Pakistan have been interpreted in conjunction with drillhole, surface geology, and Landsat data (Fig. 2.3 to 2.9). The main observations are:

(1) The thickness of the Phanerozoic sedimentary wedge at the deformation front is exceptionally high, about 10 km. The structurally duplicated sedimentary section 114 km north of the deformation front is about 15 km thick. This thickness includes more than

7 km of carbonate-dominated Paleozoic to Eocene strata (compared to about 1 km for the same age strata in the Salt Range).

(2) The gross geometry of the overthrust wedge, including gentle topography (<1°) and broad width (> 250 km), is compatible with that proposed by Davis and Engelder (1985) for thrust belts developed over a weak decollement. However, evidence suggests that the Eocambrian evaporite sequence that provides an effective zone of decoupling at the base of the section in the Salt Range and Potwar Plateau (Lillie et al, 1987; Jaume and Lillie, 1988) may not be present underneath the Sulaiman fold belt. This evidence includes: (a) absence of salt related structures such as tight anticlines, broad synclines and disharmonic folding (Lillie and Yousaf, 1986; Davis and Engelder, 1985); (b) the closest observation of the Eocambrian evaporites in seismic lines is about 200 km east of the deformation front (Humayon et al, 1991). The effective zone of decoupling in Sulaiman may be in pelitic rocks or fine carbonates above the crystalline basement at a depth of more than 10 to 15 km. Depth of the detachment is constrained by seismic reflection profiles (826-LO-14 & 81-LO-2 in Fig. 2.4). At this depth, fine-grained sedimentary rocks may provide a weak decollement similar to the evaporites at a depth of 3 to 4 km (Lillie and Davis, 1990).

(3) Basement dip is about 2.5° to the north. Basement is not involved in the deformation at least as far back as the Bugti syncline (Fig. 2.3). This is based on the critical observation of the seismic data from the southern Sulaiman foredeep (Fig. 2.4). However, farther north involvement of the basement is not precluded as the nature of the crust is inferred to be transitional below the Sulaiman fold belt (Jadoon et al, 1989; Khurshid, 1991).

(4) The southernmost surface folds reflect a coherent stratigraphy in which older rocks are progressively exposed in the eroded cores of more northerly, tighter anticlines (molasse in Sui anticline, Eocene in Loti and Pirkoh, Paleocene in Kurdan, and Cretaceous in Tadri, Fig. 2.3). The crests of these folds are cut only by small-scale bending-movement normal faults. Seismic reflection profiles confirm that these surface folds reflect thrust faults and duplexes at depth (Fig. 2.8). Seismic reflection profiles also show that rocks exposed at the surface northwards from the Bugti syncline are structurally elevated by the overthickened, active wedge. The resultant structural relief varies from 4 to 8 km from south to north.

(5) Overall structural style is of hinterland-dipping duplexes bounded between a floor thrust near the base of the sedimentary section and a passive-roof thrust in thick Cretaceous shales. Fault related folds are exposed at the surface. Frontal broad and gentle folds (Sui and Loti), wavelength about 20 km, may be primarily formed as a result of

ductile flow of fine carbonates and pelitic rocks in the core of the anticlines at a depth of about 10 km.

(6) Total shortening parallel to the direction of tectonic transport along the duplex structures and the broad frontal folds is estimated as 76 km based on the balanced cross-section discussed later. Only a fraction of shortening (< 1 km) is accommodated by the surficial frontal folds (Sui and Loti), over a distance of about 55 km.

The details of these structures are discussed below in the context of seismic reflection profiles and the structural cross-section A-A' (Fig. 2.7, 2.8, & 2.9). This is followed by a discussion of the style of deformation and deposition in the foredeep basin, progressive deformation and crustal shortening.

BALANCED STRUCTURAL CROSS-SECTION

Drillholes data from the frontal part of the Sulaiman fold belt and adjacent foredeep (Fig. 2.4), have been provided to Oregon State University by the Hydrocarbon Development Institute of Pakistan (HDIP), Texaco and Amoco. A composite seismic line (bold lines in Fig. 2.4) has been constructed to project subsurface data onto a 174-km-long balanced structural cross-section (A-A' in Fig. 2.3). A balanced structural cross-section is one that can be retrodeformed; thus it provides an opportunity to evaluate if the solution is geologically reasonable (Bally et al, 1966; Dahlstrom, 1969a, 1970; Gwinn, 1970; Woodward et al, 1989). A line length balancing technique is applied to the section except at the base of the broad frontal folds where the technique is invalid due to the ductile flow of the rocks in the core of the gentle anticline. The section was balanced in this basal zone using an area balancing technique (Dahlstrom, 1969a; Woodward et al, 1989).

Surface and Seismic Expression of the Frontal Region

Most of the seismic lines in figure 2.4 include data of 5 seconds two way travel time, yet basement could only be seen in OGDC line SAJ-22 from the Sulaiman foredeep (Fig. 2.7). Seismic reflection profiles show that the stratigraphic thickness about 60 km southeast of the deformation front is about 6 km (Fig. 2.3, 2.7). Stratigraphic thickness increases toward north along the cross-section (A-A' in Fig. 2) and is about 10 km at the deformation front. Stratigraphic thickness of 10 km at the deformation front of the

Sulaiman fold belt contrasts with the 2-3 km stratigraphic thickness of the wedge in front of the Salt Range/Potwar Plateau (Lillie et al, 1987).

It is important to locate the basement on the seismic lines from the frontal Sulaiman fold belt and adjacent foredeep in order to evaluate: (a) the total thickness of the sedimentary wedge above the crystalline basement; (b) the basement slope, which is important for inferring the mechanism of thrusting (Davis et al, 1983; Davis and Engelder, 1985); and (c) basement structures, their genesis, and effect on thrusting. The top of the basement can be seen only on OGDC line SAJ-22 within the foredeep (Fig. 2.7). Just south of the Sulaiman front, the basement reaches depths beyond the 5 sec two-way travel time of the other available seismic lines. However, the basement configuration for the frontal Sulaiman Ranges (Fig. 2.8 & 2.9) has been interpreted by extrapolating the layercake stratigraphy into the thrust belt from the frontal regions and adjacent foredeep using seismic lines (ZU-10, ZU-7/7E, LO-14 in Fig. 2.4, 2.7 and 2.8). Given an average basement slope (ß) of 2.5°, PreCambrian to Quaternary rocks that are about 6 km thick in the foredeep at Mari (Fig. 2.9) thicken stratigraphically to about 10 km at the deformation front. This section attains a thickness of about 15 km below the Tadri structure 114 km north of the deformation front. Planar stratigraphy and gentle and broad structures (Sui and Loti folds), as far north as the Bugti syncline are inferred to reflect planar basement. However, the presence of rift-related features of the Tethyan margin is not precluded, as transitional crust of about 25 km is inferred by Bouguer gravity modelling at the deformation front (Jadoon et al, 1990a).

Prominent reflections from the sedimentary wedge come from Eocene and Paleocene limestones, Cretaceous sandstone and limestone, and from the top and base of the massive Jurassic limestone. At the surface, progressively older strata are exposed towards the hinterland in the cores of doubly plunging anticlines (Fig. 2.3). Boreholes through the frontal folds, including Pirkoh anticline (Fig. 2.2, 2.4, &2.9), penetrate a normal stratigraphic sequence for about 3000 m and reach upper Cretaceous rocks. In the Mari gas field in the foredeep, a normal stratigraphic sequence of about 3300 m from Siwalik to Cretaceous (lower Goru) has been drilled (Fig. 2.4). This sequence includes about 2100 m of Cretaceous, 800 m of Eocene and Paleocene, and about 500 m of molasse strata (Kamran and Ranki, 1987). All units of the carbonate-dominated sequence thicken to the north on the seismic lines except the Cretaceous. North of the Pirkoh anticline, two wells drilled by Amoco to a depth of 1826 and 2455 m on the Tadri and Jandran structures respectively, penetrated a normal stratigraphic sequence of Cretaceous and Jurassic rocks. Deeper wells would have demonstrated repeated stratigraphy or elevated basement if the thin-skinned model is incorrect. Molasse strata thin toward the

Figure 2.4. Map of seismic and well data. See Figs. 2.2 and 2.3 for location. Bold lines were used to prepare a composite seismic reflection profile and to project subsurface data onto the balanced cross-section AA´ (Fig. 2.9). Crystalline basement is recognized about 30 km south of the deformation front on seismic line SAJ-22. Well abbreviations: G = Giandari-1; J = Jandran; K = Kandkot-2; L = Loti-2; M = Mari-2; Pk = Pirkoh-2; S = Sui-1; T = Tadri Main; U = Uch-1.

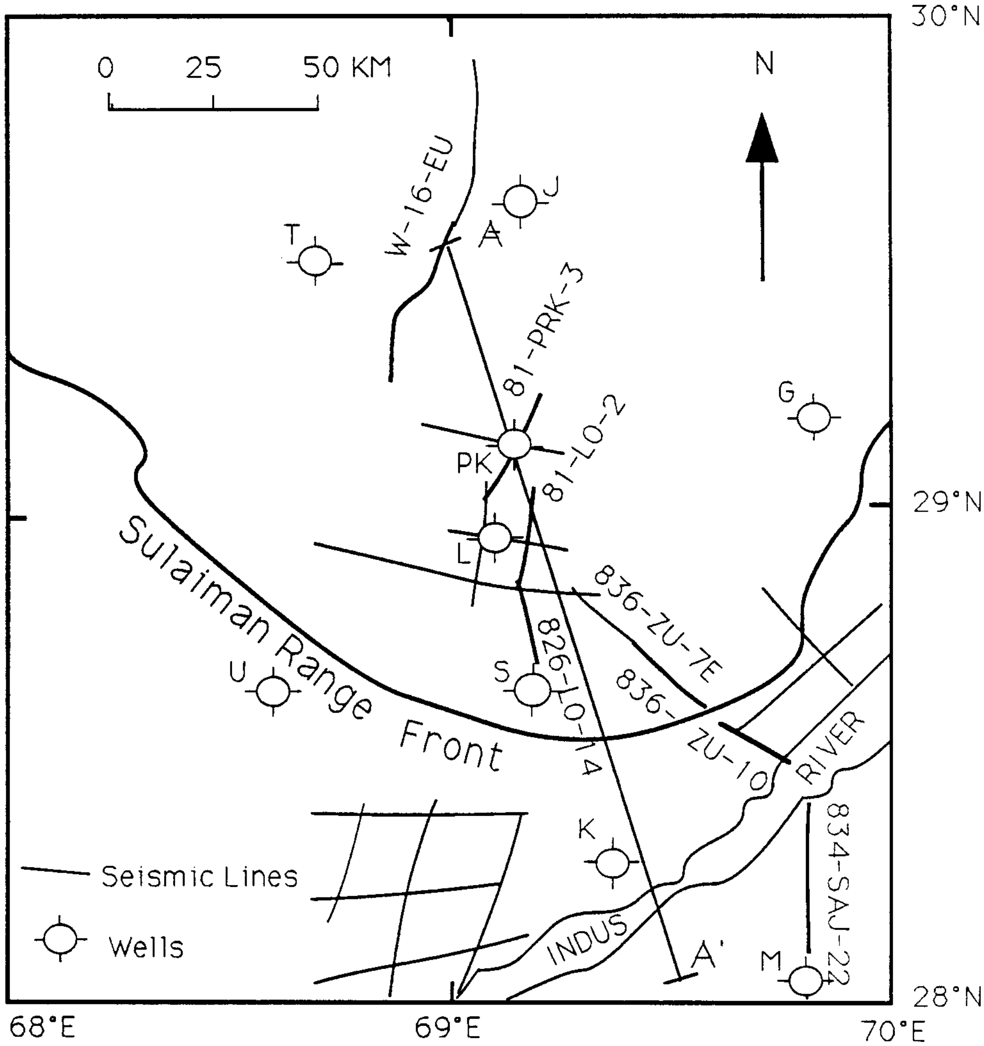

30°N
0 25 50 KM
N
W-16-EU
J
T
A
81-PRK-3
G
81-LO-2
PK
29°N
81-LO-2
L
Sulaiman Range Front
836-ZU-7E
826-LO-14
U
S
836-ZU-10
RIVER
K
834-SAJ-22
Seismic Lines
Wells
INDUS
A'
M
28°N
68°E
69°E
70°E

Figure 2.4

Figure 2.5. Structural cross-sections from the western Sulaiman fold belt CC′ and northern Kirthar Ranges DD′ (modified from Banks and Warburton, 1986). A) Passive-roof duplex geometry with a floor thrust at the base of the sedimentary section and a passive-roof thrust in the Ghazij (Eocene) and Goru (Cretaceous) Formations. B) An antiformal stack duplex and the associated foredeep with 7 km of molasse sediments. A forward facing monocline is the surface expression of the duplex. See figure 2 for location of cross-sections. Stippled and clear patterns represent molasse (Neogene) and platform strata (Eocene to Cretaceous) respectively that are a part of the roof-sequence. Brick pattern representing Jurassic to PreCambrian rocks is a part of the duplex-sequence. Random lines show crystalline basement. RT = Roof thrust.

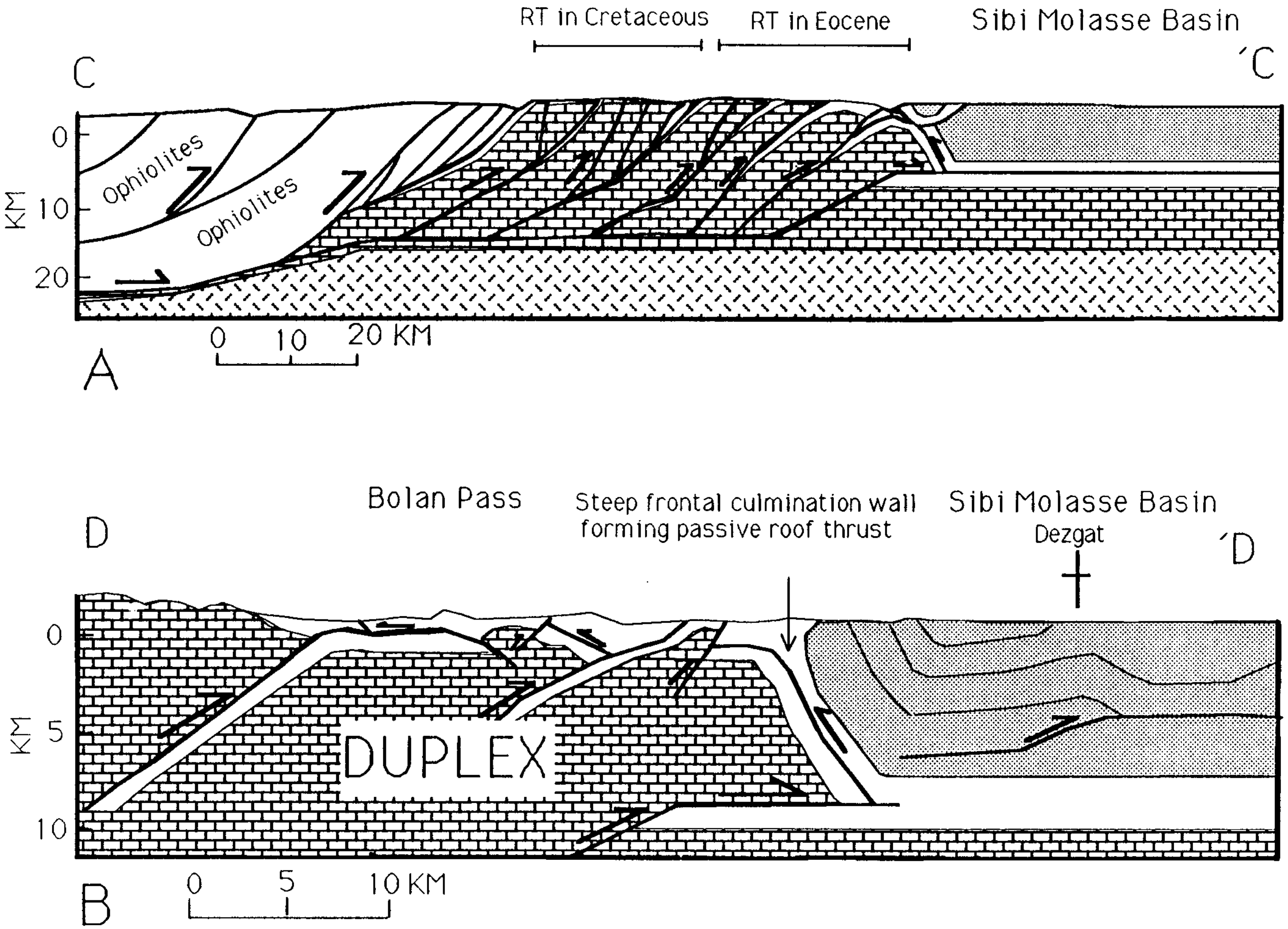
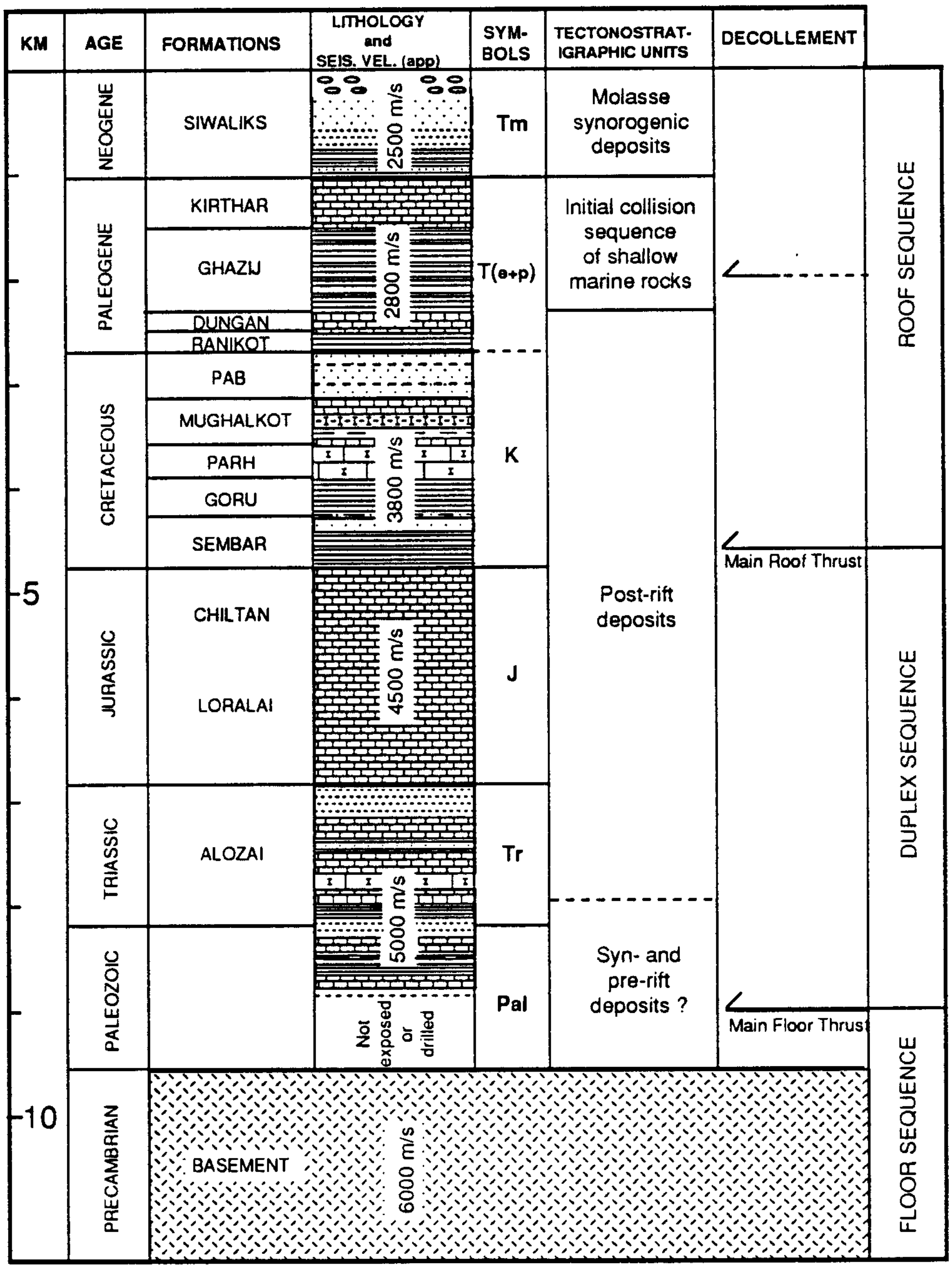

RT in Cretaceous
RT in Eocene
Sibi Molasse Basin
C
´C
0
10
20
KM
Ophiolites
Ophiolites
0 10 20 KM
A
Bolan Pass
Steep frontal culmination wall
forming passive roof thrust
Sibi Molasse Basin
Dezgat
D
´D
0
5
10
KM
DUPLEX
0 5 10 KM
B

Figure 2.5

Figure 2.6. Simplified stratigraphic column of the frontal Sulaiman fold belt. Approximate seismic velocities are estimates based on thicknesses from the well data, sonic logs, and converting stacking velocities from seismic lines to interval velocities. Detachment horizons are shown with a duplex sequence below and a roof sequence above Cretaceous shales.



KM
AGE
FORMATIONS
LITHOLOGY and SEIS. VEL. (app)
SYM-BOLS
TECTONOSTRAT-IGRAPHIC UNITS
DECOLLEMENT
NEOGENE
SIWALIKS
2500 m/s
Tm
Molasse synorogenic deposits
PALEOGENE
KIRTHAR
GHAZIJ
DUNGAN
RANIKOT
2800 m/s
T(e+p)
Initial collision sequence of shallow marine rocks
ROOF SEQUENCE
CRETACEOUS
PAB
MUGHALKOT
PARH
GORU
SEMBAR
3800 m/s
K
Main Roof Thrust
5
JURASSIC
CHILTAN
LORALAI
4500 m/s
J
Post-rift deposits
DUPLEX SEQUENCE
TRIASSIC
ALOZAI
Tr
PALEOZOIC
5000 m/s
Not exposed or drilled
Pal
Syn- and pre-rift deposits ?
Main Floor Thrust
10
PRECAMBRIAN
BASEMENT
6000 m/s
FLOOR SEQUENCE

Figure 2.6

hinterland, with sporadic outcrops in the cores of synclines (Fig. 2.9). This implies that the molasse sediments are continually reworked and redeposited toward the foreland. In effect the molasse sediments migrate through time toward the foreland in response to southward translation of thrust sheets. 745 m of molasse strata were encountered in the Kandkot-2 well and 593 m in the Mari-2 gas field well in the foredeep. Total thickness of the molasse strata from the frontal Sulaiman foredeep is about 2400 m (Fig. 2.9). Thickness of the molasse strata in the Sibi molasse basin along the western Sulaiman and northern Kirthar Ranges is about 7000 m (Banks and Warburton, 1986; Fig. 2.5). In the eastern Sulaiman foredeep, about 3500 m of molasse sediments are present (Humayon et al, 1991). At the western and eastern margins of the Sulaiman Lobe, the surface expression of the deformation front is a foreland-dipping monocline (Fig. 2.5) above a hinterland-dipping duplex sequence (Banks and Warburton, 1986; Humayon et al, 1991).

The surface expression of structures from the frontal part of the Sulaiman fold belt (Sui and Loti) is two broad and very gentle, doubly-plunging anticlines with half wavelengths of about 20 km. The half wavelengths of intervening synclines are 6 to 8 km. Surface expression of the southerly limb of the third folded structure (Pirkoh) is a foreland-dipping monocline with dips between 35° and 70°. The top of this structure has almost horizontal strata over a distance of about 16 km (Fig. 2.8 & 2.9). Further north, less open folds of smaller wavelengths exist. Only Siwalik, Eocene and Paleocene rocks are exposed along the line of the section. From south to north, progressively older strata occupy the hinge zones of the anticlines as structurally deeper levels are exposed. In addition to folds, normal and tear(?) faults are exposed at the surface. The Ridge, Saini Mund, and Pezbugi Nala faults on the Loti structure have a dip-slip offset of about 20 meters and possibly displace the axis of the Loti syncline several hundred meters by a strike-slip component (Fig. 2.3).

The seismic expression of structures along the line of cross-section is of broad concentric anticlines (Sui and Loti) and more complex structures to the north (Fig. 2.8). The Sui and Loti folds maintain their layer parallel thickness and wavelength on the seismic lines, unlike typical concentric folds (Dahlstrom, 1969b), where anticlines become tighter and synclines become broader at depth. I infer that the space in the cores of these anticlines is occupied by the ductile flow of fine carbonates and pelitic rocks (similar to exposed in the hinterland) as a result of tectonic compression of the southward-propagating thrust sheet at depths of 10 to 15 km. Concentric folding is seen as deep as 5 seconds of two way travel time data on the seismic lines across the Sui and Loti structures (Fig. 2.8 and 2.9). Basement is expected between 5 and 6 seconds. This implies that virtually all the Phanerozoic section is decoupled from the crystalline basement, with the decollement near the base of the wedge. North of Bugti syncline, exposed rocks have a structural relief of about 4 km in the Pirkoh and about 8 km in the Tadri structures (Fig. 2.8 & 2.9). The style of deformation above a detachment in Cretaceous shales is of passive folding in the roof thrust sheet; below, it is a duplex sequence of Jurassic and older rocks. A passive-roof backthrust in the Cretaceous Sembar shale accommodates forward movement of this duplex sequence (Fig. 2.6, 2.8, & 2.9). Consequently, there is not a thrust fault at the surface in the tectonically thickened wedge from the frontal part of the Sulaiman fold belt. A similar style of deformation is reported from the western (Banks and Warburton, 1986; Fig. 2.5) and eastern (Humayon et al, 1991) Sulaiman Range, the Kohat Plateau in the Trans-Indus Salt Range (Ahmed and McElroy, 1991; McDougall and Hussain, 1991), the northern Potwar Plateau (Lillie et al, 1987; Jaswal et al, 1990) and from other foreland fold and thrust belts (i.e. Canadian Cordillera, Price, 1981, 1986; Jones, 1982; Appalachians, Boyer and Elliot, 1982; Mitra, 1986; the Scottish Highlands, Elliot and Johnson, 1980; Hossack et al, 1984; Williams, 1985; the Alps, Boyer and Elliot, 1982; the Papua, New Gunea, Hobson, 1986; and the Taiwan thrust belt, Suppe, 1980, 1983).

The deformed section is about 129 km long and restores to an undeformed length of about 205 km which gives a shortening of about 76 km (Fig. 2.9). This is very unevenly divided between the duplexes (75 km shortening), and broad Sui and Loti frontal anticlines (<1 km shortening). The central Sulaiman shortening determined here is similar to the 95 km of shortening found by Banks and Warburton (1986) for the equivalent portion of the western Sulaiman Lobe and also to the 70 km of shortening in the Kohat Plateau south of the Main Boundary thrust (McDougall and Hussain, 1991).

STRUCTURAL STYLE AND DEVELOPMENT

Style of Deformation

The Sulaiman lobe is an actively deforming fold belt that thickens northwestwards over a basement slope of 2.5°. About 10 km of undeformed platform and molasse strata, as measured at the deformation front, are thickened in a thrust wedge to about 15 km, 129 km north of the deformation front. This thickness is interpreted in this paper as due to thin skinned structural duplication. However, the major thrust faults that are responsible for this thickening of the wedge do not crop out at the surface. Balanced and retrodeformed cross-sections based on seismic control suggest that the style of deformation is a duplex sequence of massive Jurassic limestone and older rocks probably detached from the crystalline basement along a decollement, and a roof-sequence of thick Cretaceous shales overlying these duplexes on a passive-backthrust.

Surface and subsurface observations show a progradation of thrusting toward the foreland, as predicted by Davis et al (1983). The interpreted chronology of structures is: (1) growth of broad, concentric fault tip folds in the foreland; (2) propagation of the basal decollement and uplift of the passive-roof sequence above a backthrust near the deformation front; (3) propagation of the duplexes as critical taper is achieved; and (4) tear faults and extensional normal faults within the tectonically overthickened wedge. The currently active Sui and Loti anticlines in front of the hinterland-dipping duplexes are the present fault tip folds. Their cores are filled primarily by the flow of fine carbonates/pelitic rocks at depths of more than 10 km where conditions of incipient metamorphism might be expected. This suggests that the folding precedes thrusting in the frontal Sulaiman fold belt. The extensional normal faults (for example, Pezbugi fault) are considered typical bending-movement structures formed above the neutral plane of folding and may initiate simultaneously with the initial folding.

The structural style of the roof-sequence is of fault-related folds (hybrid folds of Mitra, 1986) of variable tightness, symmetry, and extent as a result of ramp spacing, relative displacement along adjacent thrusts, degree of overlap, and final position of the cut-off point with respect to the next ramp. Hybrid folds from the frontal Sulaiman fold belt, using the terminology of Boyer and Elliot (1982), Butler (1982), Suppe (1983), Boyer (1986), and Mitra (1986), are classified as 1) fault-bend folds; 2) leading edge, ramp overlap anticlines; 3) intraplate anticlines; and 4) overlapping ramp anticlines. Specific examples of each type of structure are discussed below.

(1) Fault-bend fold. The Pirkoh anticline is a foreland verging fault-bend (box) fold. It has a broad hinge zone which exposes flat-lying, Eocene Pirkoh limestone at its core over a distance of about 16 km. This reflects the considerable displacement of the hanging wall beyond the footwall cutoff point. Displacement between cut-off points is about 20.5 km along a horse with a total length of about 45 km. The surface expression of the southern limb is of a monocline with dips of 35° to 70°S (Fig. 2.9). The northern limb of Pirkoh, over the ramp, is overlapped by another fault-related fold (Danda anticline), and so is not exposed at the surface. The topographic slope along the line of section north of Pirkoh is towards the hinterland.

The Pirkoh anticline is the youngest fault-bend fold in this part of the actively deforming Sulaiman fold belt. The locus of shallow seismicity in the Sulaiman lobe is the Bugti syncline just south of Pirkoh anticline (Quittmeyer et al, 1979; Quittmeyer et al, 1984). This corresponds closely with the tip of the fault beneath the fold (Fig. 2.9). Epicenters of two events of magnitude between 6 to 7 are located on Loti and Sui anticlines (Quittmeyer et al, 1979). Determination of the depths of these seismic events could best determine if the active deformation is now concentrated along the decollement below and ahead of the Pirkoh duplex or along the roofthrust or otherwise along basement related faults.

(2) Leading edge, ramp overlap anticlines. The Danda anticline, north of Pirkoh, is a comparatively tight structure with a wavelength of about 4 km. The hanging wall cut-off points of this anticline are displaced to a distance of 24.5 km over the equivalent footwall cut-offs. The present expression of the Danda structure is a result of the total displacement along the Pirkoh duplex below and ahead of the Danda fault-bend fold , and the degree of overlap over the ramp along which the Pirkoh duplex steps upsection to propagate toward the foreland.

(3) Intraplate folds. Boyer (1986) describes how intraplate folds accommodate shortening strain within the body of the thrust sheet and are commonly cored by faults that propagate from the basal thrust fault. Examples have been presented from the Elk Horn anticline in the Montana thrust belt, Bear Creek anticline in southeast Idaho, the Wyoming thrust belt, and from the Valley and Ridge Province of Pennsylvania (Boyer, 1986). The Kurdan anticline, with a wavelength of about 8-10 km and a steeper northern limb, is interpreted as an intraplate fold cored by a hinterland verging, passive-backthrust that propagates from a within-stack decollement surface. A relative shortening of about 3.8 km has occurred as a result of forward wedging of Triassic and older strata underneath the passive-backthrust.

(4) Overlapping ramp anticlines (anticlinal stack). In the core of the Tadri anticline, Cretaceous rocks are exposed (Fig. 2.3), with an uplift of about 8 km. This is interpreted to be a result of differential displacement along 2 horses (Fig. 2.9). Out of the total shortening of about 26.3 km, 10 km has occurred within the lower, and younger, horse (Fig. 2.9). The result is completely overlapping ramp anticlines, as envisioned by Mitra (1986).

Passive-Roof Sequence and Backthrust

A passive-roof sequence is a normal stratigraphic sequence separated from the duplex sequence by a roof thrust that remains stationary above a forward-propagating thrust sheet (Banks and Warburton, 1986). To a minor extent shortening of the duplex sequence is accommodated in the roof sequence by uplift and folding. Banks and

Figure 2.7. Seismic line about 30 km south of the deformation front showing the stratigraphic section and crystalline basement at a depth of 3-4 seconds on two way travel time (about 6-8 km depth). See figure 2.4 for location. Line SAJ-22 is 8-40 Hz, migrated vibroseis source, recorded in 1983 by OGDC and processed by Petty-Ray Geophysical Company.

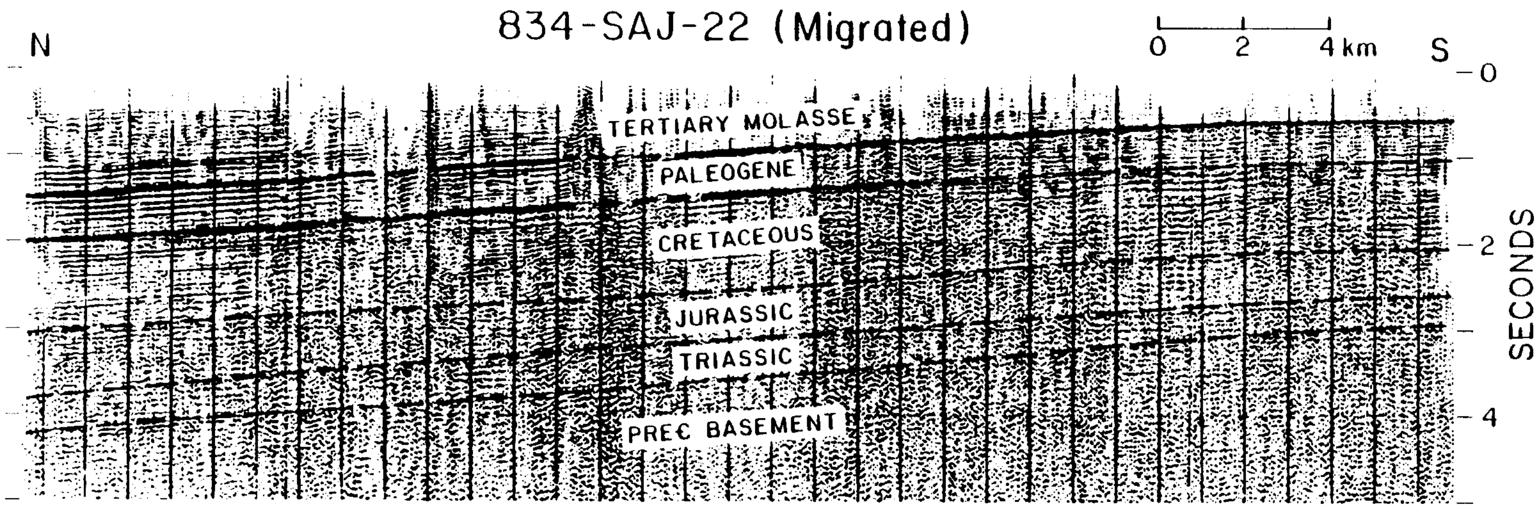
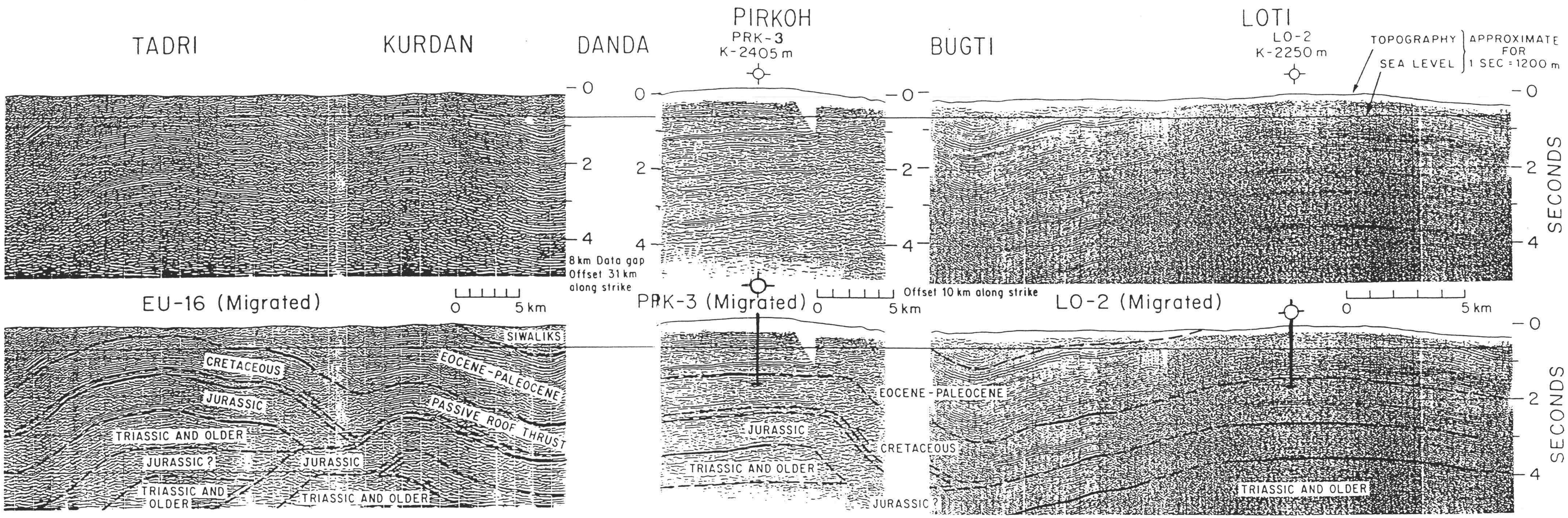

834-SAJ-22 (Migrated)
N
S
0
2
4 km
TERTIARY MOLASSE
PALEOGENE
CRETACEOUS
JURASSIC
TRIASSIC
PREЄ BASEMENT
0
2
4
SECONDS

Figure 2.7

Figure 2.8. Composite uninterpreted and interpreted seismic line from the frontal Sulaiman fold belt. Tertiary shallow marine strata and Siwaliks molasse are exposed at the surface. Basement is below 5 seconds on 2-way travel time. The section shows duplex bounded by a passive-roof thrust in Cretaceous shales and a floor thrust probably just above crystalline basement. The tip of the blind thrust extends below the Loti anticline (Fig. 2.9). Note that concentric folding is the structural style of the broad Loti anticline; the space in the core of the broad folds (Loti and Sui) may be filled by ductile flow of fine carbonates or fine structures (small scale duplex) within a decollement zone at a depth of more than 10 km. Line 81-LO-2 is 24-fold, migrated dynamite source, recorded and processed in 1981 by OGDC. Line 816-PRK-3 is 24 fold, migrated dynamite source, recorded by OGDC in December 1980 to January 1981 and processed by Geophysical Service Inc. Azaiba, Oman. Line W16-EU is 10-40 Hz, migrated vibroseis source, recorded and precessed by Western Geophysical Company of America in 1975. Lines are tied along strike. See figure 2.9 for geological details of seismic data gap between lines W16-EU and 816-PRK-3. Horizontal scale differs between all the lines.



TADRI
KURDAN
DANDA
PIRKOH
PRK-3
K-2405 m
BUGTI
LOTI
LO-2
K-2250 m
TOPOGRAPHY
SEA LEVEL
APPROXIMATE FOR 1 SEC = 1200 m
SECONDS
8 km Data gap
Offset 31 km along strike
Offset 10 km along strike
EU-16 (Migrated)
PRK-3 (Migrated)
LO-2 (Migrated)
0 5 km
SIWALIKS
CRETACEOUS
EOCENE-PALEOCENE
JURASSIC
PASSIVE ROOF THRUST
TRIASSIC AND OLDER
JURASSIC ?
TRIASSIC AND OLDER
CRETACEOUS

Figure 2.8

Figure 2.9. Actual and restored, NNW-SSE geological cross-section of the frontal Sulaiman fold belt. A) Cross-section based on seismic reflection profiles, surface geology, borehole, and LANDSAT data. B) Balanced cross-section involving further interpretation of the lower figure. C) Retrodeformed cross-section based on AA'. Roof-sequence extends continually for a distance of about 150 km north of the tip of the duplex and is not cut by a major backthrust. An equal amount of the roof-sequence must be removed primarily by erosion in the Loralai valley in the hinterland. In the current balanced section (top figure) only the shortening associated with the folds in the roof-sequence is shown. Seismic data has been projected from the bold lines in Fig. 2.4 on to the cross-section AA′ in Fig. 2.3. Names identifying the individual horses in the duplex sequence are from the individual mountains (shown on Fig. 2.3), formed by the duplex propagation.

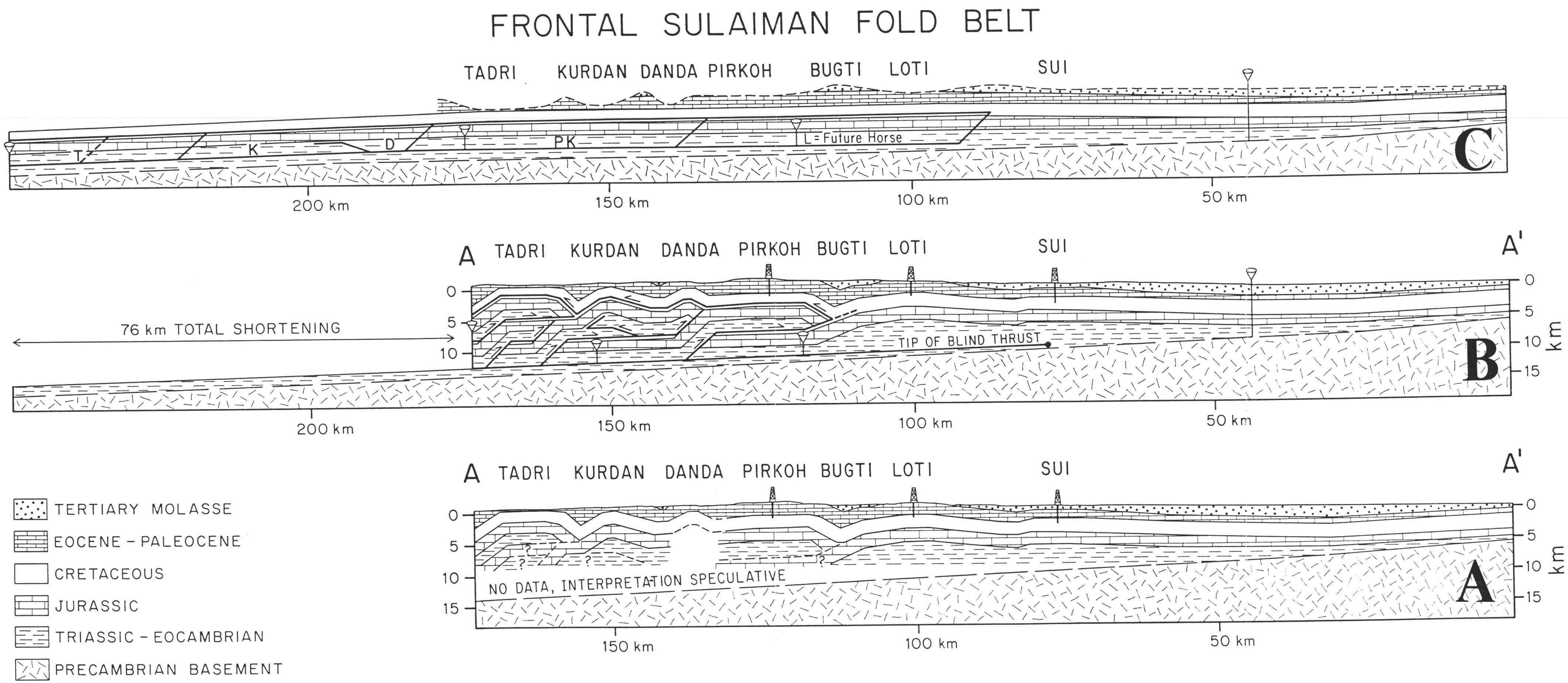

FRONTAL SULAIMAN FOLD BELT
TADRI KURDAN DANDA PIRKOH BUGTI LOTI SUI
T
K
D
PK
L = Future Horse
C
200 km
150 km
100 km
50 km
A TADRI KURDAN DANDA PIRKOH BUGTI LOTI SUI A'
76 km TOTAL SHORTENING
TIP OF BLIND THRUST
0
5
10
15
km
B
A TADRI KURDAN DANDA PIRKOH BUGTI LOTI SUI A'
NO DATA, INTERPRETATION SPECULATIVE
A
TERTIARY MOLASSE
EOCENE - PALEOCENE
CRETACEOUS
JURASSIC
TRIASSIC - EOCAMBRIAN
PRECAMBRIAN BASEMENT

Figure 2.9

Warburton (1986) suggest that a roof-sequence, instead of extending over a large number of duplex horses, may be imbricated, thus an equal amount of roof sequence is removed primarily by erosion along overstep backthrusts (see their Fig. 2.7). How far a passive-roof sequence may extend has not yet been resolved. In Taiwan the length of passive-roof sequence is about 14 km (Suppe, 1980). Jones (1982) predicts that a 50 km of relative backthrust sequence may have extended over the Alberta foothills. A retrodeformed geological cross-section from the thick Papua New Guinea thrust belt shows a major passive-roof sequence of more than 120 km length (Hobson, 1986). The Brooks Range of Alaska provides another example of a continuous passive-roof sequence that may extend several hundred of kilometers across the regional strike (Vann et al, 1986).

In the frontal Sulaiman fold belt, the passive-roof sequence of Cretaceous and younger rocks covers the entire area studied over a continuous roof backthrust. Along the line of section studied, the preserved extent of this roof sequence is about 60 km. Information from the Sulaiman fold belt shows that the roof sequence extends over a distance of about 150 km northwards from the tip of the duplex in the Bugti syncline and no major cross-cutting backthrust has yet been discovered through reconaissance mapping. Finally, the base of the roof sequence (thick Cretaceous shale) is exposed at the surface in the broad Loralai Valley where majority of the roof sequence is removed by erosion. This example suggests that in the initial stages of its evolution, a passive-roof sequence may extend over several duplex horses without overstep backthrusts cross-cutting the roof sequence.

Duplex Development, Orogenic Contraction, and Deposition in the Foredeep Molasse Basin

Sequential restoration of the balanced structural cross-section from the active Sulaiman fold-and-thrust belt provides an opportunity to unravel the progressive deformation and provide information on the deposition, uplift, and forward migration of the foredeep basin. The following is a chronological description of the evolution along the cross-section A-A' in Fig. 2.10.

(A) Erosion of molasse and platform sediments from southward migrating thrust sheets in the Loralai and Kohlu areas north of the studied section (Fig. 2.2) developed a molasse basin that thinned toward the foreland. Deposition continued until depth to the basement became sufficient for the decollement to propagate southward. This initiated a thrust sheet of massive Jurassic limestone and older strata, bounded between a floor and a roof thrust, that stepped up-section and slid along thick Cretaceous shale at the base of the roof sequence for 16.25 km (Fig. 2.10A-B).

(B) Surface expression of the duplex became a foreland dipping monocline. Location of the ramp in this case is arbitrary, positioned only for balancing purposes. The displacement of 16.25 km (2.10-B) within this duplex is the amount of shortening along line A-A'. With uplift, the foredeep basin migrated further south, and reworking of the molasse sediments thickened the foredeep wedge. A topographic slope of 2.8° was produced on the section and may have provided critical taper. The 2nd thrust sheet (T) stepped upsection below the tip of the 1st duplex and flattened along the shale horizon at the base of the Cretaceous (Fig. 2.10B-C).

(C) A displacement of 10 km of thrust slice T produced an antiformal stack, Tadri, and a 6.5 km deep molasse basin filled with reworked molasse eroded from structures north of the section. A modern example of this geometry exists in the northern Kirthar and western Sulaiman ranges, where Jurassic limestone is exposed 9 km above its normal stratigraphic level in the foreland. Where as in the adjacent foredeep Sibi basin contains 7 km of molasse strata (Banks and Warburton, 1986; Fig. 2.5B). Development of the Tadri antiformal stack and extreme steepening of the passive-roof thrust impeded backthrust motion. Continuous uplift allowed erosion through the deformed molasse strata and into the Eocene Kirthar limestone. When sufficient topographic slope was developed (~4° in Fig. 2.10C), the frictional resistance at the base and top of the thrust wedge was overcome, and the roof thrust propagated southward (Fig. 2.10C).

(D) Within the duplex sequence, wedging of an intraplate thrust (between K and D and below the passive-roofthrust) produced the hinterland verging Kurdan intraplate fold (Fig. 2.10D). The fault in the core of the Kurdan anticline remained passive during 3.75 km of foreland-directed displacement of the Kurdan intraplate thrust sheet (K) along the basal detachment. See present geometry and position of this fold in figure 2.9A'. Uplift and translation of the Kurdan structure shifted the deformation front farther south. A modern analog to this situation is the Sibi molasse basin in front of the western Sulaiman/Kirthar Ranges (Fig. 2.5), and the foredeep in front of the eastern Sulaiman Ranges.

(E) Propagation of the sole detachment continued in front of the antiformal stack. The length of the horse (K + D) is about 42 km. This detached sequence stepped upsection and was translated along a flat for a distance of about 25 km (Fig. 2.10D-E). Successively older rocks were exposed in the cores of the fault-related anticlines. The composite seismic reflection line suggest that top of Cretaceous sandstone in the Tadri

Figure 2.10. Sequential restoration of duplex development in the frontal part of the active Sulaiman fold belt along the line of cross-section A-A´ (Fig. 2.3). Area balancing is done below the Triassic over the two frontal broad folds (Fig. 2.9). The current basement slope (β) 2.5° is considered to remain constant in the reconstruction. Topographic slope (α) changes at each step to create the suitable taper to overcome the frictional resistance at the base of the wedge allowing the duplex to propagate towards the foreland. At each stage the deformation front (DF) progressively moves towards the foreland and continental molasse strata are constantly reeroded and redoposited to thicken the foredeep wedge. See text for discussion of cross-sections A-G on this figure.

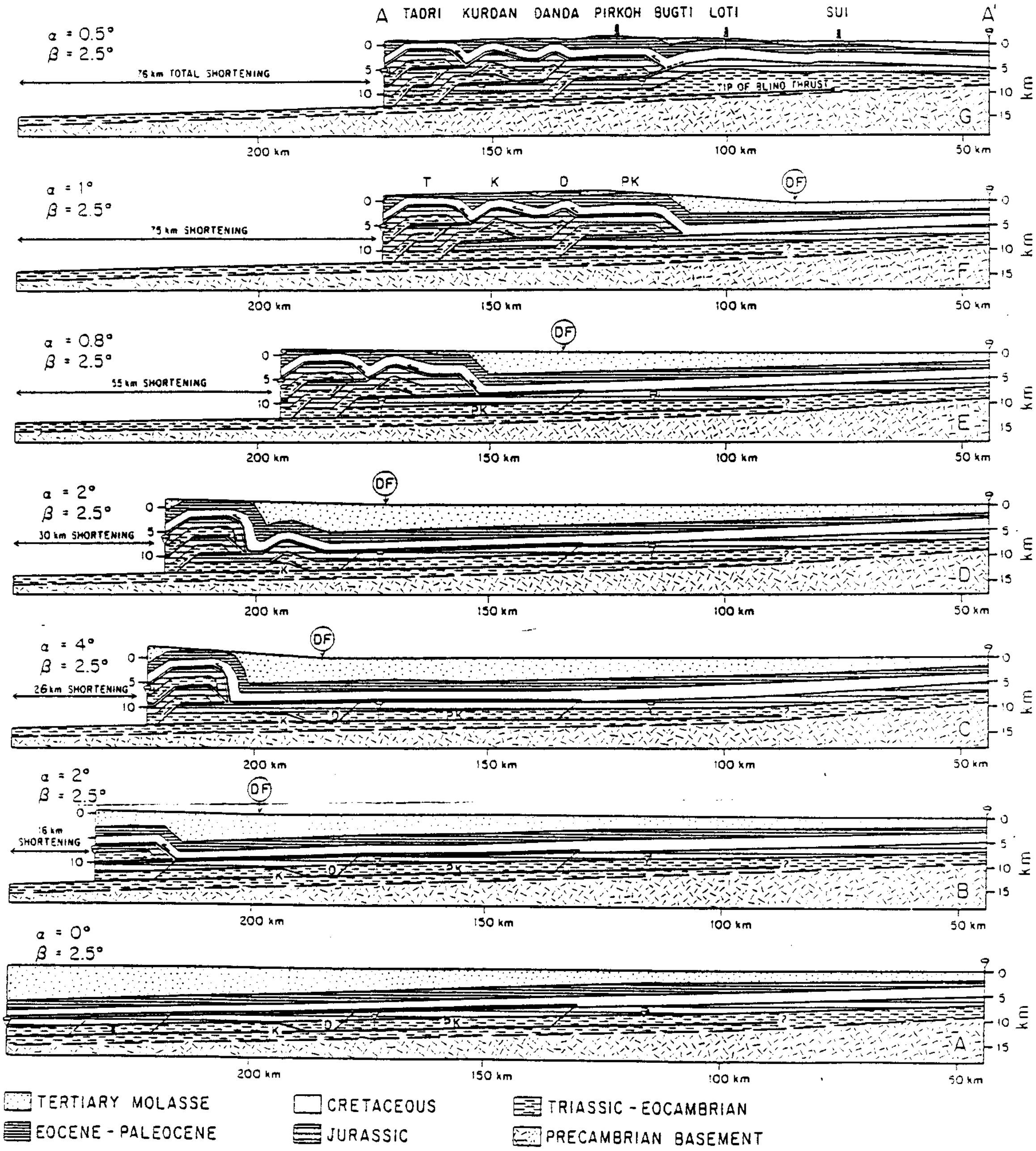

A TADRI KURDAN DANDA PIRKOH BUGTI LOTI SUI A'
α = 0.5°
β = 2.5°
75 km TOTAL SHORTENING
TIP OF BLIND THRUST
α = 1°
β = 2.5°
75 km SHORTENING
T K D PK
DF
α = 0.8°
β = 2.5°
55 km SHORTENING
α = 2°
β = 2.5°
30 km SHORTENING
α = 4°
β = 2.5°
26 km SHORTENING
α = 2°
β = 2.5°
16 km SHORTENING
α = 0°
β = 2.5°
200 km
150 km
100 km
50 km
km
TERTIARY MOLASSE
EOCENE - PALEOCENE
CRETACEOUS
JURASSIC
TRIASSIC - EOCAMBRIAN
PRECAMBRIAN BASEMENT

Figure 2.10

structure was raised 8 km from its regional stratigraphic position. The decollement in all these stages remains at a depth of 10-15 km.

(F) The Pirkoh thrust slice (PK) stepped-up southwards in front of the Danda (D) monocline (Fig. 2.10E-F). This horse was translated for a distance of about 20 km to form the broad, fault-bend Pirkoh anticline. The surface expression of the duplex was that of a broad monocline. The topographic slope was about 1° to the south and the total displacement within the duplex sequence was about 75 km. The depositional axis of the molasse basin migrated farther toward the foreland throughout compression.

(G) The present day geometry developed by very gentle concentric folding (L and S) in front of Pirkoh anticline (Fig. 2.10G). The figure suggests that the space in the cores of these anticlines is occupied by ductile flow of fine-grained sedimentary rocks at a depth of more than 10 km, possibly involving substantial pressure solution. Extensional normal faults with a component of strike-slip displacement are the dominant surface structures along the hinge zones of the Pirkoh and Loti anticlines. The deformed section of 129 km length within the duplex sequence restores to an undeformed length of 205 km (Fig. 2.9). Total displacement is 76 km at the present day. As discussed earlier, an equal amount of roof sequence must have been removed, primarily by erosion, in the broad Loralai Valley. In this paper only the part of the shortening that was taken-up by folds in the roof sequence is balanced (Fig. 2.9c).

CONCLUSIONS

Surface and subsurface data from the southern Sulaiman lobe have been integrated to look into the structural evolution of the active Himalayan fold belt along the western margin of the Indian subcontinent. The important conclusions are summarized as follows:

(1) The gentler surface topography (<1°) and broad width (>250 km) of the Sulaiman fold belt is similar to other mountain belts underlain by a weak decollement.

(2) The compressive deformation along the frontal part of the Sulaiman fold belt is accommodated by a duplex whose floor thrust is above the crystalline basement and roof thrust is in thick Cretaceous shales. The surface expression of deformation in the duplex is fault-related folds (Pirkoh, Danda, Kurdan, and Tadri), where exposed rocks at the surface are structurally uplifted 4-8 km above their regional stratigraphic level.

(3) The roof sequence is not breached along the cross-section, suggesting that a major passive-roof thrust extends over a 60 km length along the cross-section.

(4) Progressive structural development is as follows: (a) concentric folding behind the fault tip (Sui and Loti anticlines); (b) the development of a passive-roof duplex at the deformation front; (c) forward propagation of the duplex to produce a variety of structural geometries. From south to north, these features include a fault-bend fold (Pirkoh), a leading-edge ramp-overlap anticline (Danda), an intraplate fold (Kurdan), and an anticlinal stack (Tadri). Molasse sediments have been continually reworked and the depositional axis of the foredeep basin migrated southward due to southward migration of the deformation front.

(5) Palinspastic restoration indicates a shortening of 75 km in the duplex sequence and 76 km in the entire deformed 129 km section. The restored section has a length of 205 km.

(6) Only a fraction of the shortening, <1 km, is taken up by the broad, frontal Sui and Loti anticlines. These folds, extending over a distance of 55 km in front of the main mountain belt, are concentric in the seismic lines as deep as 4 to 5 seconds two way travel time on seismic data. The basement is expected between five and six seconds on two way travel time data. The space in the cores of frontal anticlines is primarily filled by ductile flow of probably fine carbonates at depths of about 10 km, as a result of tectonic compression; implying that tip-line folding precedes faulting in the southern Sulaiman fold belt.

Mari-Bugti Pop-Up zone in the central Sulaiman fold belt, Pakistan

SECTION 3

ABSTRACT

The Sulaiman fold-and-thrust belt is an active tectonic feature of the Himalayan mountain system in Pakistan. Seismic reflection profiles, borehole, and surface geology data, and Bouguer gravity modelling suggest a "passive-roof duplex" geometry over a transitional crust related to the former passive margin of the Indian subcontinent. In the frontal part of the Sulaiman fold belt, a passive-roof sequence of Cretaceous and younger rocks is structurally uplifted. On the surface, the roof sequence displays a coherent stratigraphy over the underlying duplex sequence of Jurassic and older strata. The folds in the roof sequence reflect blind faults in the duplex sequence. The duplex style of deformation persists throughout the central Sulaiman Range. However, unlike the frontal Sulaiman fold belt, stratigraphy at the surface in the central Sulaiman Range is disrupted by long east-west and northeast-trending faults (lateral extent 10's to 100's of kilometers). These foreland and hinterland verging faults juxtapose Cretaceous rocks in the cores of tight, symmetrical anticlines against Eocene Ghazij Shale and Kirthar Limestone. According to seismic reflection data, they have only minor vertical offsets of 1-2 km and are mostly restricted to the roof sequence. As a result, Cretaceous rocks bounded between thrust faults are exposed at the surface in the cores of tight anticlines as pop-up structures. This implies that: (1) the exposed faults in the central Sulaiman fold belt are not primary structures with major shortening; and (2) recognition of these faults in the roof sequence may reflect an early stage of development of overstep backthrusts from the upper detachment (passive-backthrust).

INTRODUCTION

The broad, presently active, Sulaiman fold belt is located along the western transpressional boundary of the Indian subcontinent in Pakistan. In the central part of the Sulaiman fold belt, various workers (Hunting Survey Corporation, 1961; Kazmi and Rana, 1982) have recognized an extensive system of thrust faults. Kazmi (1979) considered this fault system, termed the Mekhtar-Kohlu fault zone, to be active based on the high level of local seismic activity (Quittmeyer et al, 1979; Chandra, 1981; Quittmeyer et al, 1984). The lateral extent, nature, and direction of vergence of these faults are not clear from prior work. Do these faults extend at depth to the base of the sedimentary wedge? Do they extend laterally for several tens and even hundreds of kilometers and accommodate major shortening in the broad (>300 km) Sulaiman fold belt or, alternatively, are they secondary structures?

A correct understanding of these structures is critical to developing an overall model of Sulaiman structure. One model, based on surface reconnaissance mapping and Landsat data, interprets the range in terms of a series of imbricate, forward-verging thrust sheets which break the surface as these faults (Bannert et al, 1989). An alternate model suggests that the surface of the fold belt is dominated by an extensive passive-roof backthrust system (Banks and Warburton, 1986; Izatt, 1990). Recent studies on the tectonic evolution of the Sulaiman fold belt that integrate surface geology with seismic reflection profiles and borehole data (Humayon et al, 1991, Jadoon et al, 1991) provide a chance to test these models, particularly in the Mekhtar-Kohlu fault zone. The purposes of this paper are: (1) to determine the nature of these faults; and (2) to establish the relationship between the surface structures (mostly tight anticlines) and deep structure in the central Sulaiman fold belt.

TECTONIC FRAMEWORK

The lobate Sulaiman fold belt is the broadest (>300 km) foreland fold-and-thrust belt of the Himalayan mountain system. Various workers including Abdul-Gawad (1971), Sarwar and DeJong (1979), and Lawrence et al (1981) have linked the lobate geometry of the Sulaiman Lobe to oblique convergence along the western left-lateral strike-slip boundary of the Indian subcontinent. The rocks exposed in the Sulaiman fold belt are progressively younger toward the foreland. The thick (>7 km) Triassic to Paleogene stratigraphic platform sequence (Humayon et al, 1991, Jadoon et al, 1991) is bordered by Neogene molasse toward the foreland and lower Eocene-Miocene flysch in the hinterland of the Sulaiman fold belt (Fig. 3.1). Kazmi and Rana (1982) mapped folds in the frontal part and southward verging thrust faults in the hinterland of the broad Sulaiman fold belt. Bannert et al, (1989), based on Landsat interpretation, suggest that the Sulaiman fold belt consists of a series of surface exposed nappes. Banks and Warburton (1986, C-C' in Fig. 3.1) suggest a passive-roof duplex geometry for the western

Figure 3.1. The Sulaiman fold-and-thrust belt in Pakistan (modified from Kazmi and Rana, 1982). Cross-section A-B is shown in Fig. 3.2. C-C' and D-D' shows the location of the balanced cross-sections constructed by Banks and Warburton (1986) and Humayon et al (1990) respectively. E-E' and F-F' shows the location of crustal sections by Jadoon et al (1990) and Khurshid (1991) respectively. Box locates the position of figure 3.1 and Mekhtar-Kohlu fault zone (Kazmi, 1979). Abbreviations: ABT= Andari backthrust; KF = Kingri fault. Well abbreviations: G = Giandari-1; J = Jandran; K = Kandkot-2; L = Loti-2; M = Mari-2; K = Kandhkot; KR = Kotrum; PK = Pirkoh-2; S = Sui-1; SS = Sakhi Sarwar; TM = Tadri Main; U = Uch-1; Z = Zin.

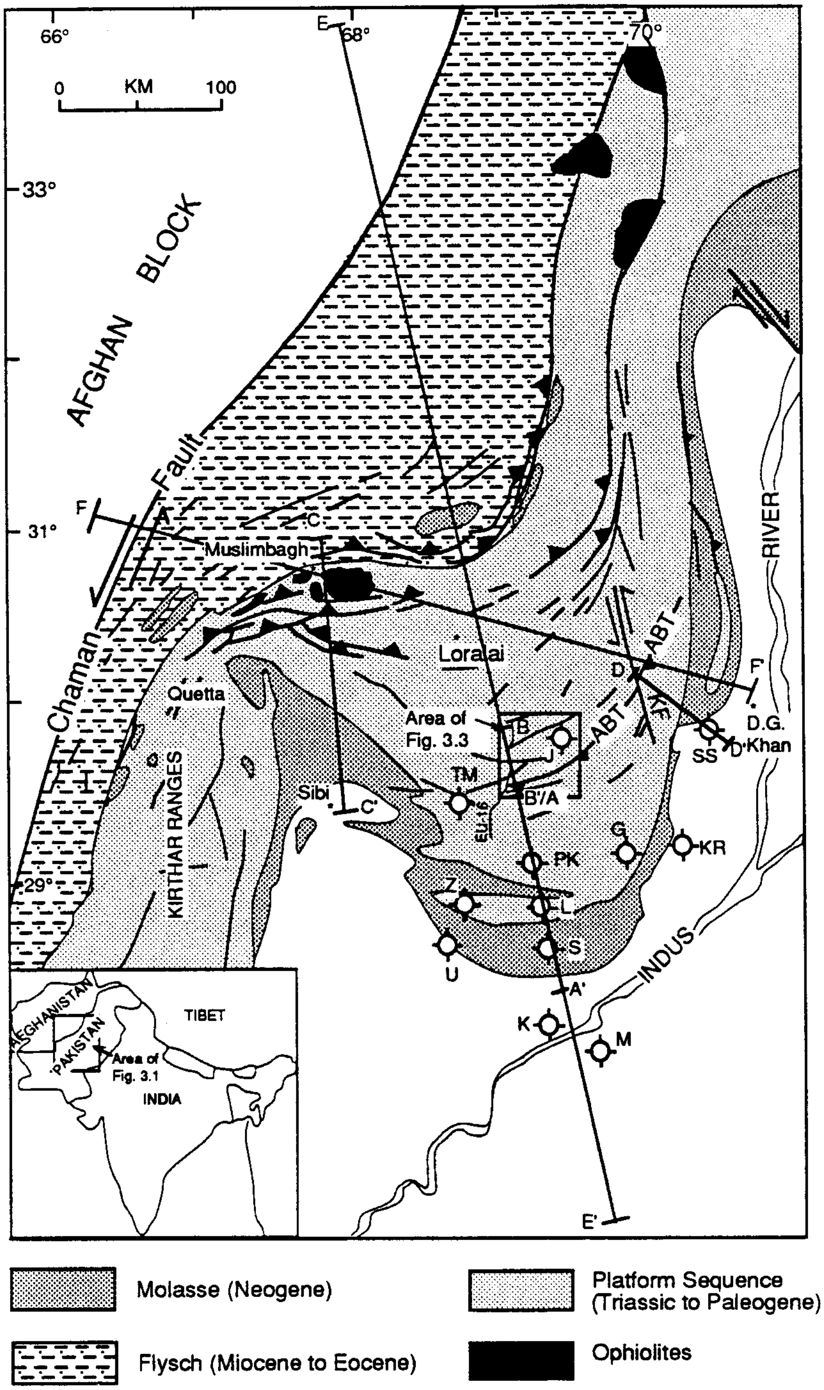

66°
68°
70°
0 KM 100
33°
31°
29°
AFGHAN BLOCK
Chaman Fault
Muslimbagh
Loralai
Quetta
KIRTHAR RANGES
Sibi
Area of Fig. 3.3
TM
EU-16
ABT
KF
D.G. Khan
SS
PK
G
KR
Z
L
S
U
K
M
INDUS
RIVER
E
E'
F
F'
A'
B'/A
C
C'
D
D'
AFGHANISTAN
PAKISTAN
TIBET
INDIA
Area of Fig. 3.1
Molasse (Neogene)
Platform Sequence (Triassic to Paleogene)
Flysch (Miocene to Eocene)
Ophiolites

Figure 3.1

Figure 3.2. Balanced structural cross-section from the frontal (AA' in Fig. 3.1) and central (BB' in Fig. 3.1 & 3.3) part of the Sulaiman fold belt. A-A' is modified from Jadoon et al (1991). Seismic coverage in this paper is in figure 3.4 and 3.5. Notice the duplex style of deformation with a major passive-backthrust in Cretaceous shales, broad duplex related folds in the roof sequence at the surface in the frontal Sulaiman fold belt (FSFB), and secondary structures in the central Sulaiman fold belt (CSFB). See figures 3.3, 3.4 and 3.5 for details over CSFB.

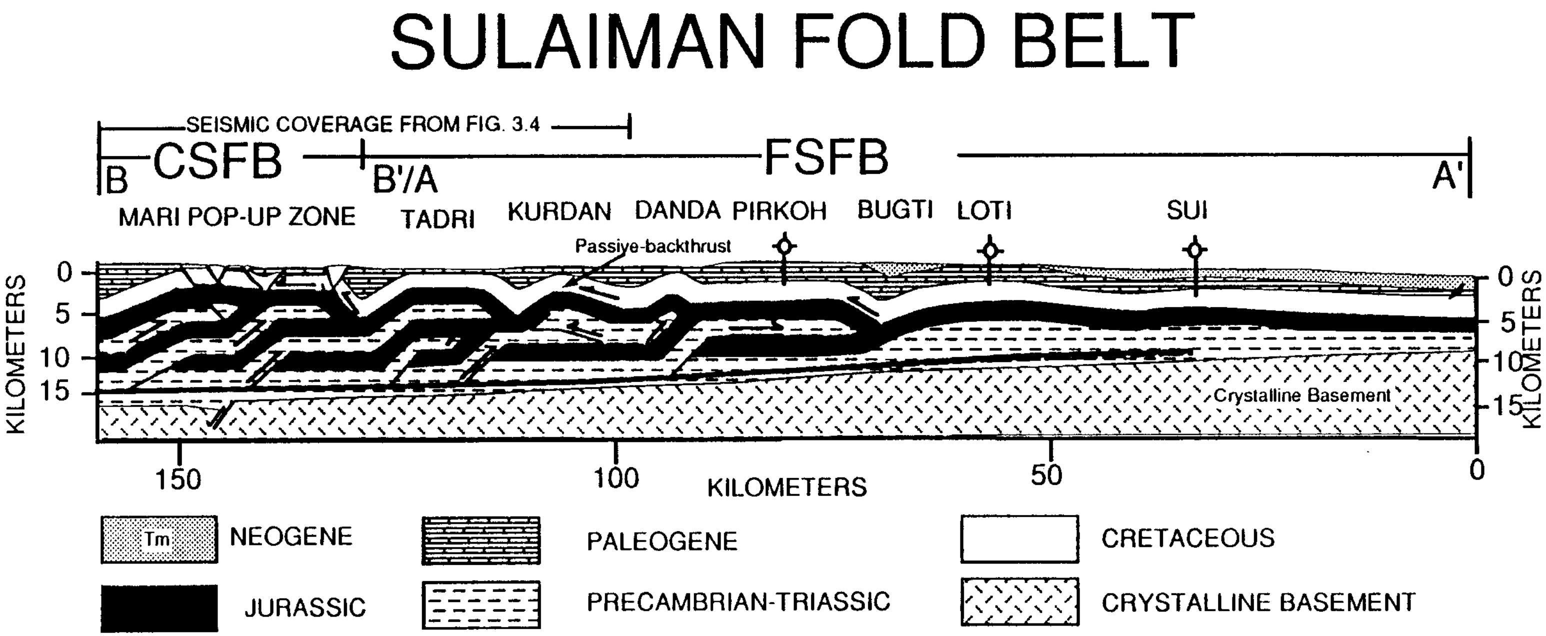

SULAIMAN FOLD BELT
SEISMIC COVERAGE FROM FIG. 3.4
B
CSFB
B'/A
FSFB
A'
MARI POP-UP ZONE
TADRI
KURDAN
DANDA
PIRKOH
BUGTI
LOTI
SUI
Passive-backthrust
KILOMETERS
0
5
10
15
Crystalline Basement
150
100
50
0
KILOMETERS
Tm
NEOGENE
PALEOGENE
CRETACEOUS
JURASSIC
PRECAMBRIAN-TRIASSIC
CRYSTALLINE BASEMENT

Figure 3.2

Sulaiman and the northern Kirthar ranges. Jadoon et al (1991, A-A' in Fig. 3.1) and Humayon et al (1991, D-D' in Fig. 3.1) integrated seismic reflection profiles and borehole, Landsat, and surface geology data from eastern and frontal part of the Sulaiman fold belt. On this basis, they drew balanced structural cross-sections that favor a thin-skinned model with duplex style of deformation. The Paleozoic to Jurassic duplex sequence is separated from the roof sequence by a major passive-backthrust in thick Cretaceous shales (Fig. 3.2). Tear faults, such as the Kingri fault (Fig. 3.1), manifest neotectonic activity by the offset of the fold axes, faults, and uplifted and tilted Holocene gravel beds along the margin of the Sulaiman fold belt (Rowlands, 1978). Such faults also may function as lateral ramps.

Unlike the full thickness of continental crust of the Salt Range/Potwar Plateau of northern Pakistan (Lillie et al, 1987, Duroy et al, 1989), gravity modelling along crustal transects E-E' (Jadoon et al, 1990) and F-F' (Khurshid, 1991) in Fig. 3.1 suggests a transitional crust averaging about 20 km thick underneath the Sulaiman fold belt. This implies an early stage of collision of the Indian subcontinent in the Sulaiman fold belt in comparison to a more advanced stage of collision in northern Pakistan.

The initial event of collision in the Sulaiman fold belt is the emplacement of the Muslimbagh ophiolite between the late Cretaceous and early Eocene (Allemann, 1979). Renewed southward thrusting since late Oligocene-early Miocene has constantly reworked the molasse strata as the deformation front migrated farther south and east (Banks and Warburton, 1986; Waheed et al, 1988; Ahmad and Khan, 1990). Southward thrusting of the cover sediments is currently in progress. It is manifested by a pronounced topographic front, linear seismicity over the topographic front in the foreland, and various degrees of tilt in the Quaternary to Holocene molasse sediments in the frontal part of the Sulaiman fold belt. This is similar to the southward migration of the active foredeep basins of the Ganges plain in India and the Jhelum plain in Pakistan (Acharyya and Ray, 1982; Raiverman et al, 1983; Johnson et al, 1985).

FRONTAL SULAIMAN FOLD BELT

The frontal portion of the Sulaiman fold belt (Fig. 3.2) consists of broad east-west trending, doubly plunging folds. The rocks structurally uplifted to the surface in the cores of anticlines, become progressively older toward the hinterland. However, these exposed rocks everywhere show a coherent stratigraphy that is not disrupted by thrust faults.

A balanced structural cross-section (A-A' in Fig. 3.2) shows the progressive structural development of the foreland features. At the fault tip, two very large concentric buckle folds with about 25 km half wave length in a structural member about 8 km thick have amplitudes of about 1 km on Sui and 1.5 km on Loti. Limb dips do not exceed 4° on Sui and 15° on Loti. These appear to be buckle folds that develop due to ductility of the unit at the detachment horizon, that is, cores of folds are filled by ductile flow of fine carbonates within the deep detachment layer. Nearly all the approximately 10 km stratigraphic sequence at the deformation front is detached. This stack of sedimentary rocks thickens tectonically to about 15 km in the central Sulaiman.

These folds are replaced by ramp and duplex structures with a continuing extremely deep detachment level toward the north, starting with the Pirkoh anticline. Major duplexing dominates between a floor thrust just above crystalline basement and a passive-roof thrust in Cretaceous shale (Fig. 3.2). Duplexing appears to be initiated when the buckle folds reach a limiting amplitude. The Pirkoh, Danda, and Kurdan anticlines are cored by a single horse. The Tadri anticline and the Mari anticlinal zones are cored by two horses. Tadri is fundamentally an anticlinal stack.

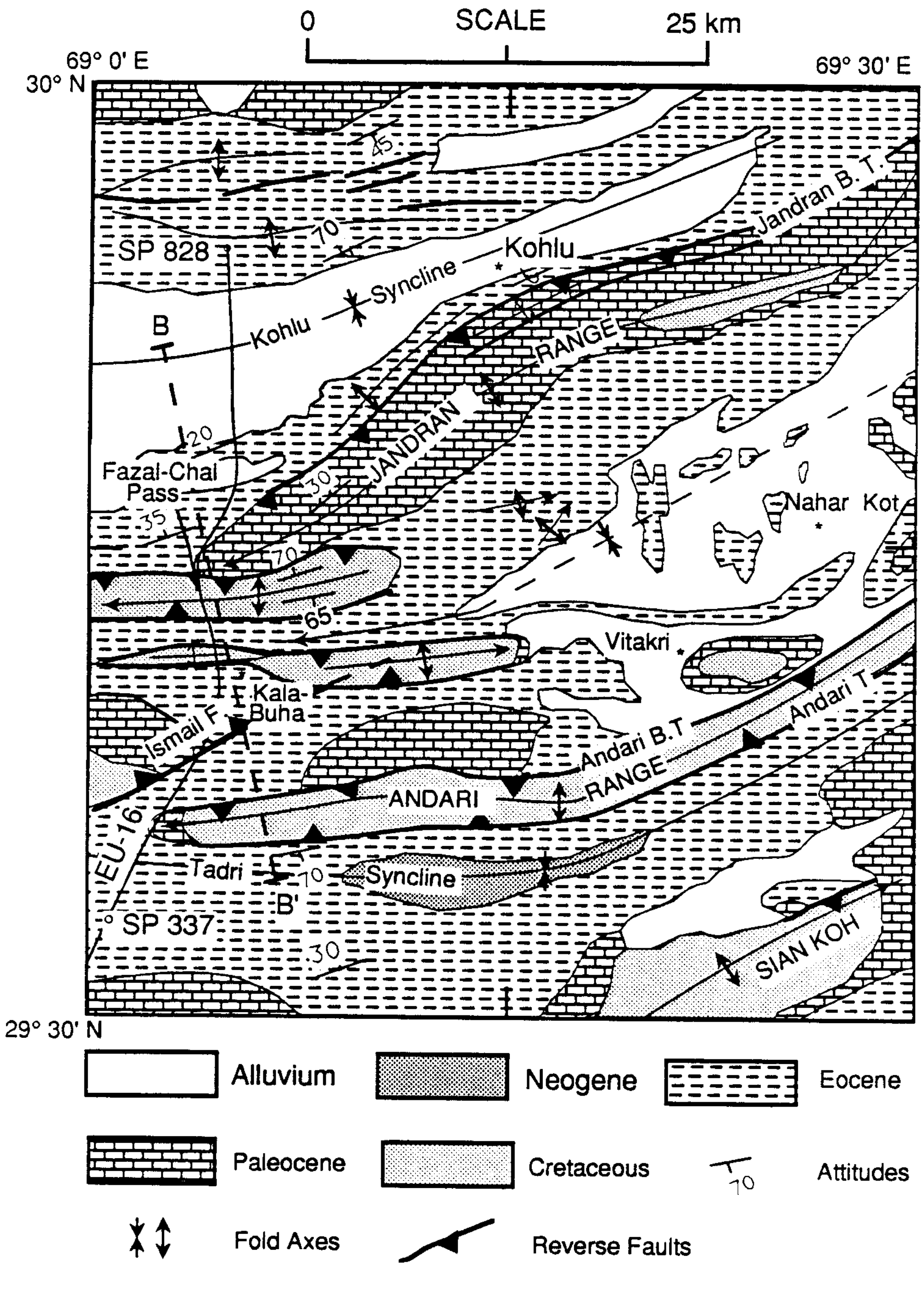
The entire portion of the section underlain by duplexes is topped by a passive-roof sequence. At and south of Tadri, faults do not cut the section above Cretaceous rocks, and fault-related folds predominate in the exposed Paleogene rocks (Fig. 3.2). The folds in the passive-roof sequence reflect the shape of the fault-bend folds in the duplex sequence (for example, Pirkoh anticline). This means that the roof sequence does not deform independently of the duplex sequence south of Tadri anticline (Fig. 3.2). The great length of the passive-roof structure in the Sulaiman fold belt remains a significant mechanical problem.

CENTRAL SULAIMAN FOLD BELT

Surface Geology

In the central part of the Sulaiman fold-and-thrust belt (Fig. 3.2) the mostly Eocene to Cretaceous exposed rocks are first seen to be cut by closely spaced faults of great lateral extent (Fig. 3.3). These faults generally parallel the traces of major fold axes. These foreland and hinterland verging thrust faults mostly juxtapose Cretaceous rocks against Eocene rocks. The largest of these is the Andari backthrust. This fault extends continually for about 170 km and is displaced laterally by the active Kingri fault in the

Figure 3.3. Geological map of the central Sulaiman fold-and-thrust belt. EU-16 shows the location of the seismic reflection line available for this study. SP = Shot Point, T = foreland verging thrust, B.T = hinterland verging backthrust.



0
SCALE
25 km
69° 0' E
69° 30' E
30° N
29° 30' N
SP 828
Kohlu
Kohlu
Syncline
Jandran B. T.
RANGE
JANDRAN
B
B'
Fazal-Chal Pass
Nahar Kot
Vitakri
Kala-Buha
Ismail F.
Andari B.T
Andari T.
RANGE
ANDARI
EU-16
Tadri
Syncline
SP 337
SIAN KOH
45
70
20
30
35
70
65
70
30
Alluvium
Neogene
Eocene
Paleocene
Cretaceous
Attitudes
Fold Axes
Reverse Faults

Figure 3.3

eastern part of the Sulaiman fold belt (Fig. 3.1 & 3.3). Jandran and Ismail faults are transverse to the main structural trend (Fig. 3.3).

The geological map (Fig. 3.3) is modified from unpublished maps of the Geological Survey of Pakistan (GSP) by Shahid Hassan Khan which is primarily based on Landsat data with some field checking. In the politically unstable area of Mari (Baluchistan) a new field check of the map by me along the location of the Amoco seismic reflection line (EU-16) was crucial due to: (1) complex structures (tight fault bounded anticlines) at the surface; and (2) poor seismic resolution along the cross-section B-B'. A new traverse from Kohlu southwards to Tadri in the central Sulaiman fold belt confirms the surface geology interpretation. Important attitudes that were used in interpreting the seismic reflection data are shown in figures 3.3, 3.4, & 3.5.

Seismic Observations

Seismic reflection line EU-16 (Fig. 3.1 & 3.4), from the central Sulaiman fold belt extends about 85 km across the strike of the fold belt and may be divided into two segments. The southern half of the seismic line, south of Tadri syncline, exhibits good seismic resolution with two relatively simple broad folds (Tadri and Kurdan, Fig. 3.4). A well drilled to a depth of 1935 m (6000') by Amoco at the Tadri structure (TM on Fig. 3.1) penetrated a normal stratigraphic sequence from Cretaceous (Fort Munro) through Jurassic (Chiltan). The entire 5 seconds of two-way travel time data shown in this seismic line are layered sedimentary rocks; basement and the detachment level are deeper than this section. Jadoon et al (1991), based on a composite seismic reflection line from the foredeep to Tadri syncline, suggest a depth of about 14 km (7 seconds) to the projected top of the crystalline basement below Tadri. Absence of faults at the surface and documented thickness of the stratigraphic section suggest that the Cretaceous and younger rocks at Tadri are uplifted, producing a structural relief of about 8 km from their regional stratigraphic level (Fig. 3.2). Jadoon et al (1991) interpreted this relief as produced by two duplex horses of Jurassic and older rocks, implying that the Tadri structure is an anticlinal stack. Seismic reflection interpretation (Fig. 3.4) shows that the folds above the passive-backthrust reflect the shape of the duplex structures below. This implies that the passive-roof sequence is not deforming independently south of the Tadri syncline.

The northern half of the seismic line, north of the Tadri syncline, loses good seismic resolution due to complex structures (closely spaced faults and tight anticlines; see Fig. 3.3 and 3.4). The reflections from the base of the Cretaceous which are located about 1.4 to 1.8 seconds on 2-way travel time data (2.5 to 3 km) below the surface are subhorizontal (Fig. 3.4 and 3.5). These rocks are uplifted about 7-8 km from their regional stratigraphic level above forward-propagating duplexes in a manner similar to the Tadri structure. In synclinal areas on the surface, mostly subhorizontal Eocene rocks are exposed except in the Tadri syncline where attitudes are steep (Fig. 3.3 and 3.4). Horizontal to subhorizontal reflections from the top of the Cretaceous at depths of 0.2 to 1 km from synclinal areas in the seismic line are consistent with the surface geology (Fig. 3.4 and 3.5). Anticlinal areas are narrow (about 1 to 3 km) with steep Cretaceous rocks juxtaposed against subhorizontal Eocene strata along foreland and hinterland verging reverse faults. In each case, these reverse faults emerge from the passive-backthrust and display a minor shortening (1-2 km) between the cut off points in the seismic data. The Ismail transverse fault (IF on Fig. 3.5) shows up at the surface as a very prominent ridge of northwest dipping massive Paleocene Dungan Limestone against Quaternary valley fills over synclinal Eocene shale. In the seismic data excellent reflections from this massive limestone show a displacement of about 1 km between the cut off points (Fig. 3.2, 3.5). Another intriguing feature is the greater thickness (about 2 km) of the Cretaceous in the seismic section (Fig. 3.4) compared to the narrow (1-3 km) areas of tight anticlines occupied by the Cretaceous rocks between these faults. In most cases the major fault in each set (Jandran, Fazal Chal, Kala Buha, and Andari) has a backthrust sense of vergence. This suggests that the faults at the surface in the central Sulaiman fold belt are shallow structures rooted in the roof thrust. Major foreland verging thrust faults are deep structures in the duplex concealed by the roof sequence. Insight into the character of this fault system has important bearing on the structural style and active tectonics of the Sulaiman fold belt. Their understanding may be important for the other active fold-and-thrust belts.

Tectonic Models

Alternate models have been presented for the general structural style of the Sulaiman fold belt (Banks and Warburton, 1986; Bannert et al, 1989; and Izatt 1990). Banks and Warburton (1986) and Izatt (1990) suggest a passive-roof duplex geometry for the western and the frontal Sulaiman fold belt, as discussed above for the frontal Sulaiman. Izatt drew very general sections across the entire range as an elaboration of Banks & Warburton's ideas. In contrast, Bannert et al (1989) propose based on Landsat data and reconnaissance mapping that the broad Sulaiman fold belt consists of a series of foreland verging imbricate thrusts, piggyback style, without major backthrusts. A similar interpretation is probably implied by the maps of Kazmi & Rana (1982) and the Hunting

Figure 3.4. Uninterpreted (A) and interpreted (B) seismic reflection line, EU-16 shown in Fig. 3.1 and 3.2. Seismic line shows that the simple folds in the passive-roof sequence south of Tadri syncline mimic the shapes of the duplex horses below them. In contrast north of the Tadri syncline pop-ups are present. These complex secondary structures are restricted to the roof sequence where it is deforming independently from the duplex sequence below . Seismic reflection line EU-16 is 10-40 Hz, migrated vibroseis source, recorded and processed by Western Geophysical Company of USA, in 1975.

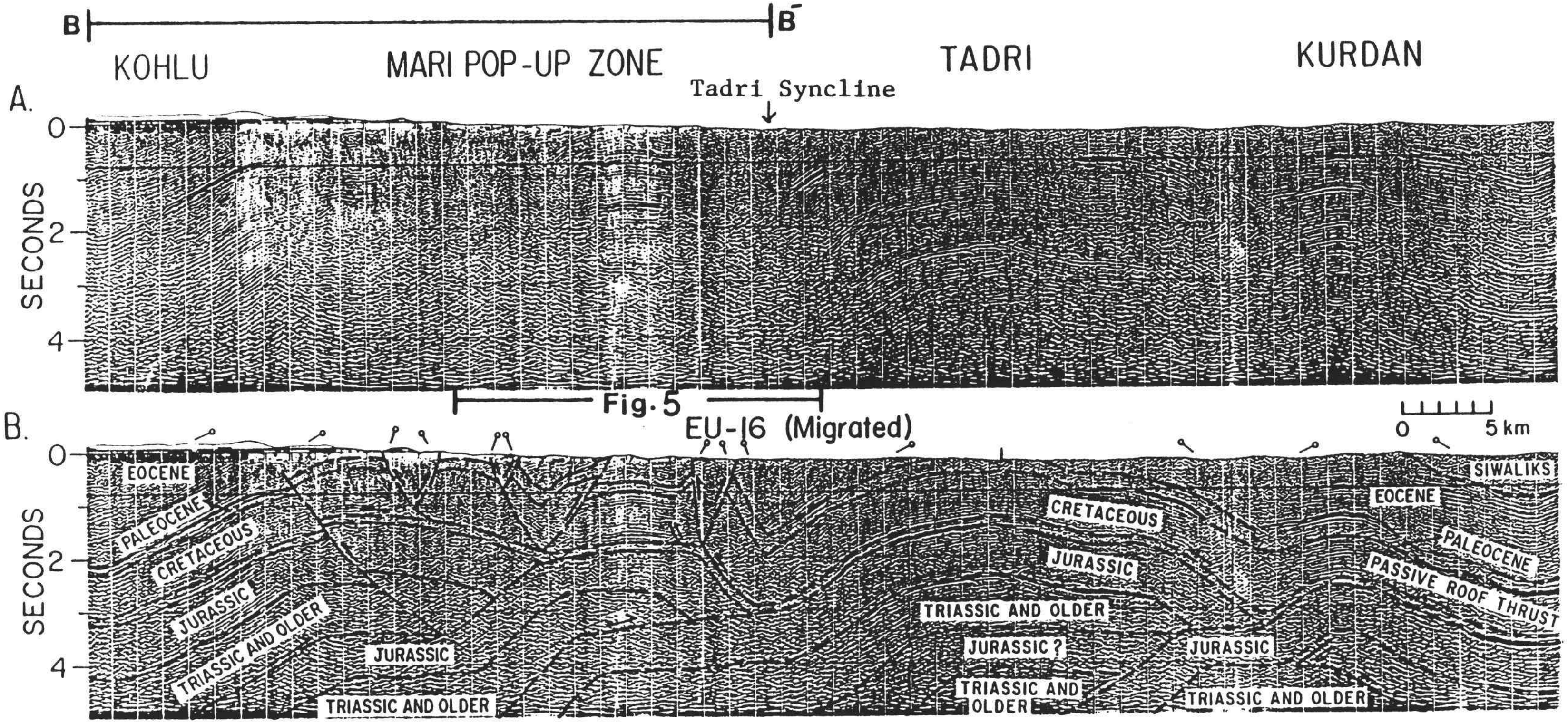

B
B'
KOHLU
MARI POP-UP ZONE
TADRI
KURDAN
A.
Tadri Syncline
SECONDS
Fig. 5
B.
EU-16 (Migrated)
0
5 km
EOCENE
PALEOCENE
CRETACEOUS
JURASSIC
TRIASSIC AND OLDER
JURASSIC
TRIASSIC AND OLDER
CRETACEOUS
JURASSIC
TRIASSIC AND OLDER
JURASSIC ?
TRIASSIC AND OLDER
JURASSIC
TRIASSIC AND OLDER
SIWALIKS
EOCENE
PALEOCENE
PASSIVE ROOF THRUST

Figure 3.4

Figure 3.5. Broader view of a part of seismic reflection line EU-16 (Fig. 3.4). The faults along Kala Buha, Andari Range (see Fig. 3.3 for location on the map view) and Ismail fault emphasize the minor displacement between cut off points along top Cretaceous and Paleocene. These secondary faults extend 10's of kilometers laterally on the surface in the Sulaiman fold belt. The Andari backthrust is the longest (170 km) recognized fault at the surface, yet total displacement between the cut off points is less than 2 km. Abbreviations: ABT = Andari Backthrust; IF = Ismail fault, Te = Eocene, Tp = Paleocene, K = Cretaceous, J = Jurassic, Tr + Pal = Triassic and older.

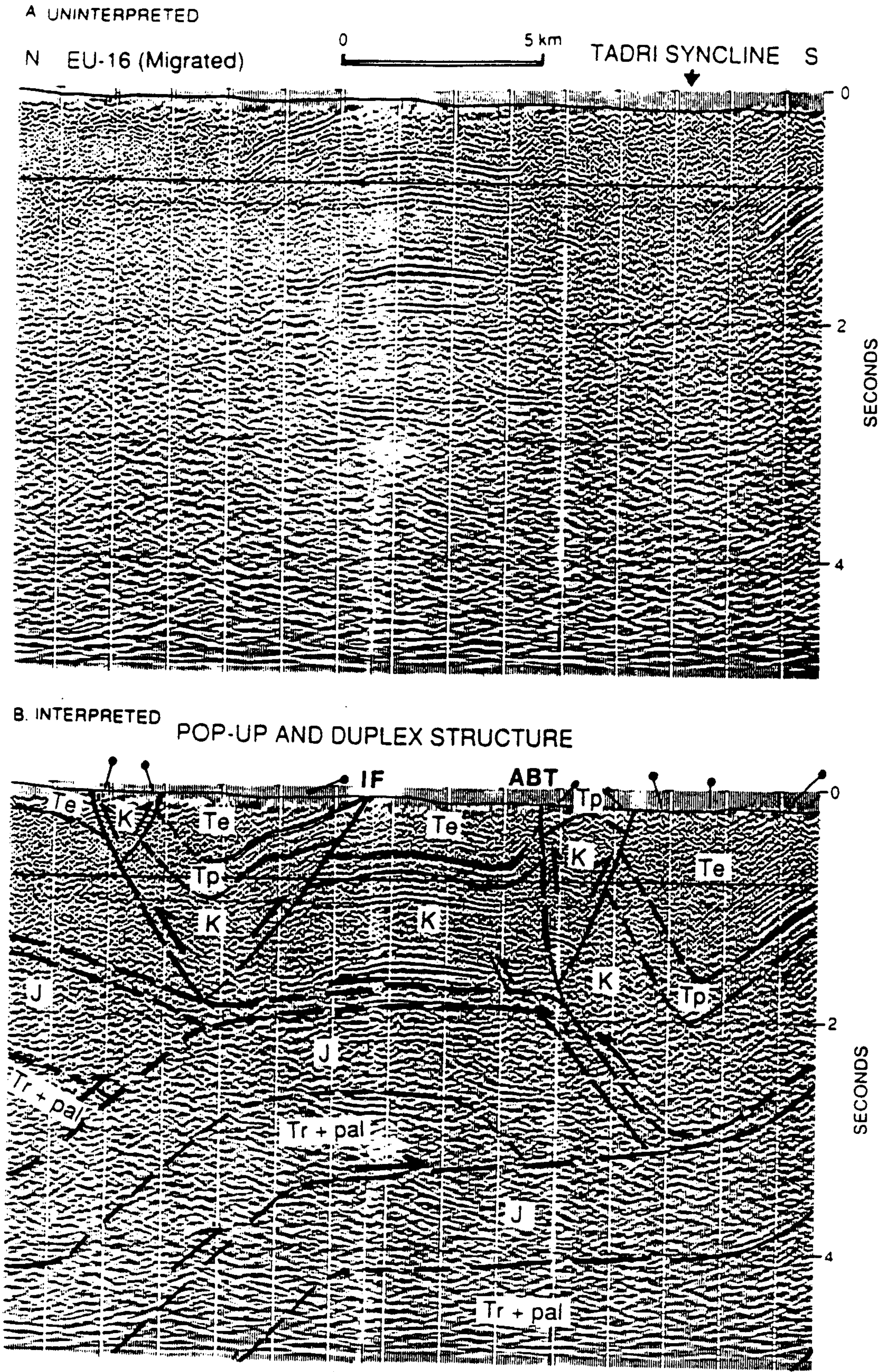

A UNINTERPRETED
N EU-16 (Migrated)
0 5 km
TADRI SYNCLINE S
0
2
4
SECONDS
B. INTERPRETED
POP-UP AND DUPLEX STRUCTURE
IF
ABT
Te
K
Te
Te
Tp
K
K
Tp
K
Te
J
K
Tp
J
Tr + pal
Tr + pal
J
Tr + pal
0
2
4
SECONDS

Figure 3.5

Survey Corporation (1961), but not presented in detail by these workers. Bannert et al (1989) propose that Eocene shale, widely distributed in the frontal and the central part of the Sulaiman fold belt, provides a favorable detachment horizon for the movement of the thrust sheets over the footwall. Both interpretations require major shortening along foreland-verging thrust faults. But in the latter case these faults must be exposed at the surface, and hinterland-verging faults are only minor antithetic features (Fig. 3.6a). This interpretation is not favored by surface geology and newly available seismic reflection data (Fig. 3.3 and 3.4) because: (1) the stratigraphy in the frontal part of the Sulaiman fold belt is never disrupted by a major thrust fault (Pirkoh thrust of Bannert et al, 1989); (2) the major surface fault in the central Sulaiman fold belt is a backthrust (Andari backthrust in Figs. 3.1, 3.3, and 3.5, part of Karmari thrust of Bannert et al, 1989); and (3) seismic reflection data show minor dip-slip displacements of 1-2 km on all the exposed faults in the central Sulaiman fold belt including the Andari backthrust (Fig. 3.5); and (4) seismic reflection data show all imbricate features to be concealed beneath a roof layer.

A balanced structural cross-section (B-B' in Fig. 3.2) shows that duplex style deformation persists in the central Sulaiman fold belt. Regardless of vergence, exposed thrust faults are restricted to the roof sequence and do not extend deeper than 3-4 km. Of these faults, each has a minor displacement of about 1-2 km, offsetting only Cretaceous and younger rocks. The Andari backthrust (Fig. 3.1) is recognized to extend laterally at least 170 km. In the eastern Sulaiman fold belt, it is encountered by Humayon et al (1991) along their balanced cross-section. They interpreted it to emerge a from passive-roof thrust. In both cases (eastern and central Sulaiman), it emerges from a depth of 4-6 km out of a syncline in front of a duplex and exhibits less than 2 kilometers of displacement. Thus most of the complex structures exposed at the surface in the central Sulaiman fold belt are secondary structures, pop-ups (terminology from Butler, 1982) between paired back- and forward-thrusts (Fazal-Chal Pass, Kala-Buha, and Andari Range), restricted to the roof sequence (Figs. 3.3, 3.4, 3.5 & 3.6b).

The presence of extraordinary faults with very long map traces but minor dip slip offset is inferred to reflect their mechanical origin. Such faults produced when major, laterally prolonged folds over persistent blind thrusts lock the passive-roof duplex and initiate accommodating faults within it. The Jandran backthrust is the major recognized exception that cuts through the upper duplex horse to a depth of about 8 km (Fig. 3.2, & 3.4). The Jandran Range anticline is a fault-propagation fold along this hinterland verging fault. Both the Ismail fault and Jandran backthrust are transverse to the trend of the main surface structures.

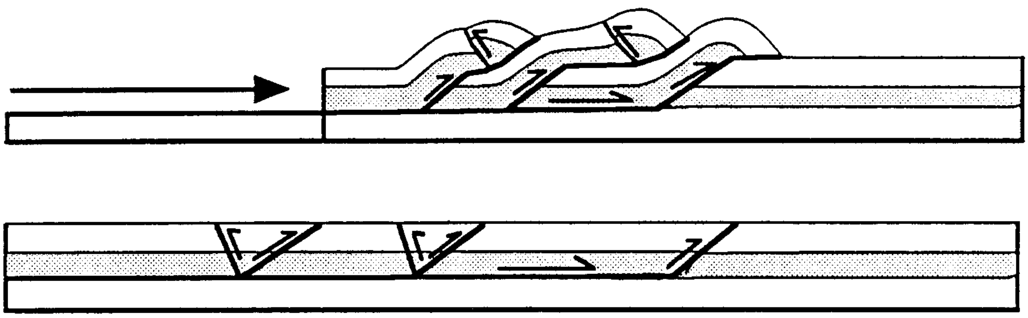
DISCUSSION

The Sulaiman fold belt exhibits the highest level of shallow seismic activity in Pakistan (Quittmeyer et al, 1979; Chandra ,1981; Quittmeyer et al, 1984). Quittmeyer et al (1979) note that the seismic activity in the Sulaiman fold belt (Quetta-Transverse Ranges) occurs in the form of two distinct bands. The southern band of activity, convex to the south, is in the region of the passive-roof duplex where there are no surface faults. Jadoon et al (1991) suggest that this activity closely follows the prominent topographic front (Pirkoh fold) over the tip of the southernmost duplex. This southern band of seismicity is probably associated with hidden faults.

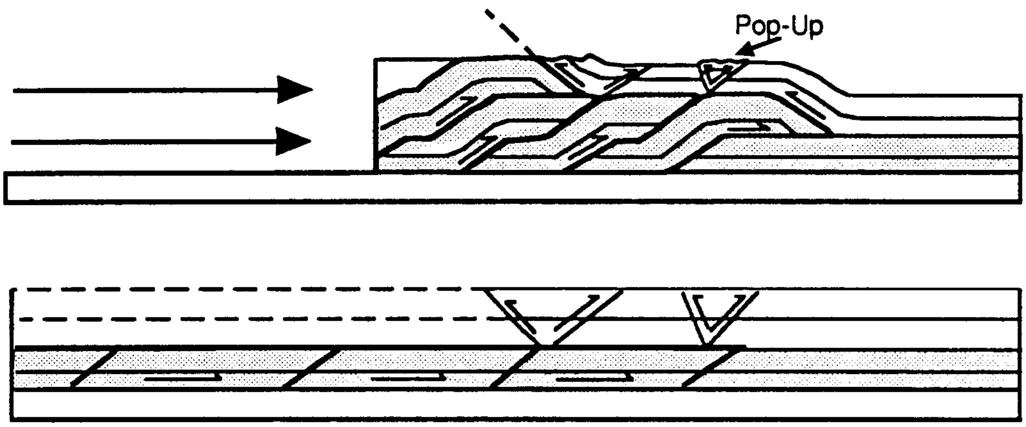
The northern band of activity parallels the mapped surface faults in the central Sulaiman fold belt (Quittmeyer et al, 1979, their Fig. 3.3). It is, however, not clear whether these earthquakes are the result of movement on a single, continuous fault or, alternatively, on a number of smaller but similarly oriented faults (Quittmeyer et al, 1979). Quittmeyer et al (1984) analyzed four moderate to large earthquakes from the central Sulaiman fold belt for focal depth and mechanism. They interpret all of these events to be shallow, 5 km depth, and to have thrust solutions. Three of these are in the eastern Sulaiman near the Kingri fault, and solution planes are significantly oblique to surface structural trends. Quittmeyer et al (1984) interpret this obliquity as suggesting that the earthquakes are produced on basement structures. The fourth earthquake is in the central Sulaiman Range near the line of section of this study and its solution plane is close to parallel to surface structural trends. My model for the structure of the Sulaiman is three layered: passive-roof layer, main duplex layer, and basement (Fig. 3.6b), and has a much thicker deformed section (duplex and roof) than was recognized previously. This suggests that all four earthquake events are related to structural activity in the top of the duplex layer and the overlying roof sequence. In the eastern Sulaiman, duplex layer structures are indeed oblique to surface structures (Humayon et al, 1991) and compatible with the earthquake solutions.

The preferred model for the structural style in the central Sulaiman fold belt (figure 3.6b) suggests that the roof sequence is presently actively deforming over the duplex sequence. The larger faults extend into the uppermost duplex and merge with the faults at the base of this structure. Shallow seismicity that is inferred to occur at about 5 km in the central Sulaiman fold belt (Quittmeyer et al, 1984) may be associated with this zone of active deformation. Thus, many of the faults exposed at the surface may be active. The lower duplex sequence is inferred to slide stably towards the foreland along a basal decollement as a coherent slab.

Figure 3.6. Tectonic models for the central Sulaiman fold-and-thrust belt of Pakistan. A) Piggyback style of deformation with secondary hinterland verging minor thrust faults. B) Passive-roof duplex style of deformation with a major backthrust in Cretaceous shales. The passive-backthrust separates duplex sequence below from secondary (pop-up) structures in the roof sequence above. Notice that the CSFB (Fig. 3.2) is referred to the Pop-Ups in this conceptual figure.



A. Imbricate Structures



B. Passive-roof Duplex Geometry

Figure 3.6

An alternative domain of active seismic deformation may be the crystalline basement. Depth to the top of the crystalline basement in the central Sulaiman fold belt is about 15 km (Fig. 3.2), below the focal depths reported (Quittmeyer et al, 1984). Crustal section (E-E' in Fig. 2.1) based on Bouguer gravity modelling infers a tectonically extended and thinned crust of about 20 km underneath the Sulaiman fold belt. This crustal section also shows a small flexural bulge along the Sulaiman foredeep. Basement normal faults associated with this former passive margin of the Indian plate could be reactivating as reverse structures. Alternatively, some seismicity may be associated with tectonic compression along a flexed Moho at about 25 km depth. Better constrained focal mechanism solutions may test these hypotheses.

Figure 3.6b shows a continuous roof sequence that overlaps several duplex horses and is emergent toward the hinterland along a passive-backthrust. This is based on an intact 150 km long passive-roof sequence in the Sulaiman fold belt (Jadoon et al, 1991). The problem of how shortening could be accommodated in the roof sequence is dealt with primarily by erosion along an emergent passive-backthrust. All other mechanisms, i. e. passive-backthrusts (Banks and Warburton, 1986), layer parallel shortening (Geiser, 1988a, 1988b), or detachment folds (Dahlstrom, 1970; Wallace, 1990) do not account for major shortening in the roof sequence. Continuous roof-sequences pose problems of shortening but are reported from the Appalachians (Boyer and Elliot, 1982; Geiser, 1988a), and the Papua New Guinea fold belts (Hobson, 1986). The pop-up structures confined to the continuous roof sequence in the central Sulaiman fold belt are recognized as secondary structures (out-of-sequence of Morley, 1988). They may show an early stage of development of passive-backthrusts. This implies that passive-backthrusts may not necessarily be present in the early stages of development of a passive-roof duplex geometry.

CONCLUSIONS

Passive-roof duplex geometry extends over at least 150 km in the Sulaiman fold belt. The roof sequence of Cretaceous and younger rocks structurally uplifted about 8 km, is deforming with hinterland vergence over anticlinal stack horses in forward verging duplexes in the central Sulaiman fold belt. Complicating structures at the surface are minor foreland and hinterland verging thrust faults, associated pop-up structures (Fazal-Chal Pass, Kala-Buha, and Andari Range tight anticlines), and transverse faults (Ismail and Jandran thrusts); most of which are restricted to the roof sequence. They extend laterally for 10's and even 100's of kilometers (Andari Range backthrust), but do not extend deep in the wedge, and have minor displacements of 1-2 km. These faults emerge from the major detachment backthrust at the base of the passive-roof sequence and are recognized as secondary (out-of-sequence) structures. Their recognition may reflect an early stage in the evolution of overstep backthrusts in the passive-roof sequence of the central Sulaiman fold belt. Overthrust backthrusts are larger magnitude passive faults which accommodate partial locking and internal shortening of the passive-roof layer. Shallow seismicity suggests that they may be active.

The Sulaiman Lobe, Pakistan: Geometry, evolution, and shortening of an active fold-and-thrust-belt over transitional crust of the ocean/continent boundary west of the Himalaya

SECTION 4

ABSTRACT

Surface and subsurface data from the Sulaiman fold-and-thrust belt are integrated to evaluate the deep structure, tectonic shortening, and crustal variation across the western margin of the Indian subcontinent. Seismic reflection data show that nearly all the 10 km thick sequence of dominantly platform (>7 km) and molasse strata is detached at the deformation front. These strata thicken tectonically to about 20 km in the hinterland of the fold belt without significant thrust faults at the surface until Loralai valley. A balanced structural cross-section suggests that tectonic uplift in the Sulaiman fold belt is a result of a thin-skinned, passive-roof duplex style of deformation. The passive-roof sequence of Cretaceous and younger rocks have a backthrust sense of vergence over foreland-propagating duplexes. It remains intact for about 150 km and becomes emergent along a passive-backthrust in the hinterland of the fold belt. The structures in the passive-roof sequence are fault-related folds in the frontal 60 km and out-of-sequence structures (secondary faults and related pop-ups) in the central Sulaiman fold belt.

A balanced structural cross-section 349 km long from the Sulaiman fold belt restores to an original length of 727 km, suggesting a maximum of 378 km of shortening in the cover strata of the Indian subcontinent. Minimum estimate of shortening is 328 km. Only 20 km of shortening is accommodated by surface faults and folds of the passive-roof sequence. Relative shortening between the roof-sequence and the duplex sequence reaches 106 km. Additional shortening along the passive backthrust is taken up by an emergent passive-backthrust in the northern Sulaiman fold belt. Calculation of displacement rates over the Sulaiman lobe (18 mm/yr) added to the resolved rate of the Chaman fault vector for the component parallel to the plate convergence direction (15 mm/yr) are close to the current plate convergence rate (37 mm/yr) along the same direction.

Modelling of a Bouguer gravity profile from the Sulaiman foredeep across the Indian/Afghan collision zone suggests that the depth to the Moho at the Sulaiman

deformation front is about 36 km. Depth to Moho increases northward with a gentle inclination of 1.1° (20 m/km) for 280 km to the hinterland, where depth to the Moho is about 42 km. About 150 km north, across the Khojak flysch zone the Moho gradient steepens abruptly to about 7.8° (136 m/km) attaining an average depth of about 57 km in eastern Afghanistan. This interpretation suggests that the Sulaiman fold belt is underlain by a transitional crust associated with the western passive margin of the Indian subcontinent.

INTRODUCTION

Hydrocarbon exploration in fold-and-thrust belts around the world is providing substantial subsurface data (seismic reflection profiles and boreholes), mainly from the mountain fronts. These data have been used effectively to understand the geometry and evolution of these important deformation belts. An important development over the last few decades has been the construction of viable balanced structural cross-sections (Dahlstrom, 1969a, Elliot, 1982; Woodward et al, 1989). Simple ramp-and-flat geometry (Rich, 1934) has been elaborated into more complex duplex-style deformation. In these structures, floor and roof faults are the major flats and multiple ramp faults between these form features named duplexes (Dahlstrom, 1970; Boyer and Elliot, 1982). Dahlstrom (1970) first used the term duplex with examples from Canadian Rockies. Subsequently, duplex structures were shown in balanced sections from other foreland fold-and-thrust belts. Some examples are the Canadian Cordillera (Thompson, 1979; Price, 1981, 1986; Jones, 1982; Morley, 1986); the Appalachians (Berg et al, 1980; Boyer and Elliot, 1982; Herman, 1984; Mitra, 1986); the Scottish Highlands (Elliot and Johnson, 1980; Hossack et al, 1984; Williams, 1985); the Alps (Boyer and Elliot, 1982); Papua New Guinea (Hobson, 1986), the Taiwan thrust belt (Suppe, 1980, 1983); and the Himalayan foreland (Banks and Warburton, 1986; Ahmed and McElroy, 1991; McDougall and Hussain, 1991; Humayon et al, 1991). The rock units above the roof fault are known as the roof sequence. In some cases, a continuous roof sequence of great length is shown in balanced structural cross-sections (Hobson, 1986). A major concern with the duplex style of deformation is how to deal with shortening in roof sequence above the duplex sequence. An answer to this question requires more data on the geometry of particular deformed zones and mechanical modelling of specific field conditions. Nonetheless, different possibilities to accommodate shortening in the roof sequence have been proposed from the western Sulaiman fold belt, the Appalachians, and the Brooks Range, Alaska (Banks and

Warburton, 1986; Geiser, 1988a, 1988b; Wallace, 1990). Many uncertainties about these structures may be expected to be resolved with insight into successive stages of structural development in fold-and-thrust belts.

In the northern Himalayas of Pakistan, India, and Nepal, the involvement of crystalline basement in collision records an advanced and thick-skinned stage of continental collision (Powell, 1979; Seeber and Armbruster, 1979; Seeber et al, 1981; Tahirkheli and Jan, 1979; Gansser, 1981; Tapponier, 1982; Yeats and Lawrence, 1984; Molnar, 1984; Mattauer, 1986; Searle, 1986; Baig, 1990, Lillie, 1991). Paleomagnetic data suggest that the Indian subcontinent have drifted about 2000 km to the north since collision at 50-55 Ma (Patriot and Achache, 1984; Klootwijk et al, 1985). In the main Himalayas, primary structures (i.e duplexes in the cover strata) have either been overprinted by secondary structures (Searle et al, 1987) or destroyed by uplift and erosion due to advanced collision. Lack of data generates problems in clarifying our understanding of both the geometry and the chronology of structures. Missing sections affect evaluation of the amount of internal shortening in the cover strata. Present estimates of shortening related to the western Himalayas in northern Pakistan are 300 km (Lawrence et al, 1989; Bob Lawrence, personnel communication), 475 km (Coward and Butler, 1985), and 500 km (Izatt, 1990). Malinconico (1989) approached the problem of the shortening with estimates of crustal volume and suggested crustal shortening between 570 and 1,140 km. All of these are still less than the 2,000 km of shortening since Eocene time calculated for the central Himalaya/Tibitean Plateau region largely from paleomagnetic data (Molnar, 1984; Klootwijk et al, 1985).

The Sulaiman lobe (Sarwar and DeJong, 1979) to the west of the Himalayas is a broad (> 300 km) fold-and-thrust belt that is tectonically active (Fig. 4.1). Its surface geology is dominated by continental platform and shallow marine rocks bordered by ophiolites and flysch in the rear and continental molasse strata in the foredeep (Fig. 4.2). This broad fold belt is going through an early stage of continental convergence. Nowhere are continental basement rocks exposed in the fold-and-thrust belt or interpreted to be involved in the thrusting at depth. Herein, the belt is interpreted to overlie transitional or oceanic crust of a previously extended continental margin (Khurshid, 1991; Lillie, 1991). In contrast, the main Himalayas have continental crust of nearly twice normal thickness as interpreted using surface wave dispersion (Gupta and Narain, 1967; Chun and Yoshii, 1977) and Bouguer gravity data (Lillie et al, 1987; Duroy et al, 1989). In addition, basement rocks are exposed at the surface above the Main Central thrust (LeFort, 1975).

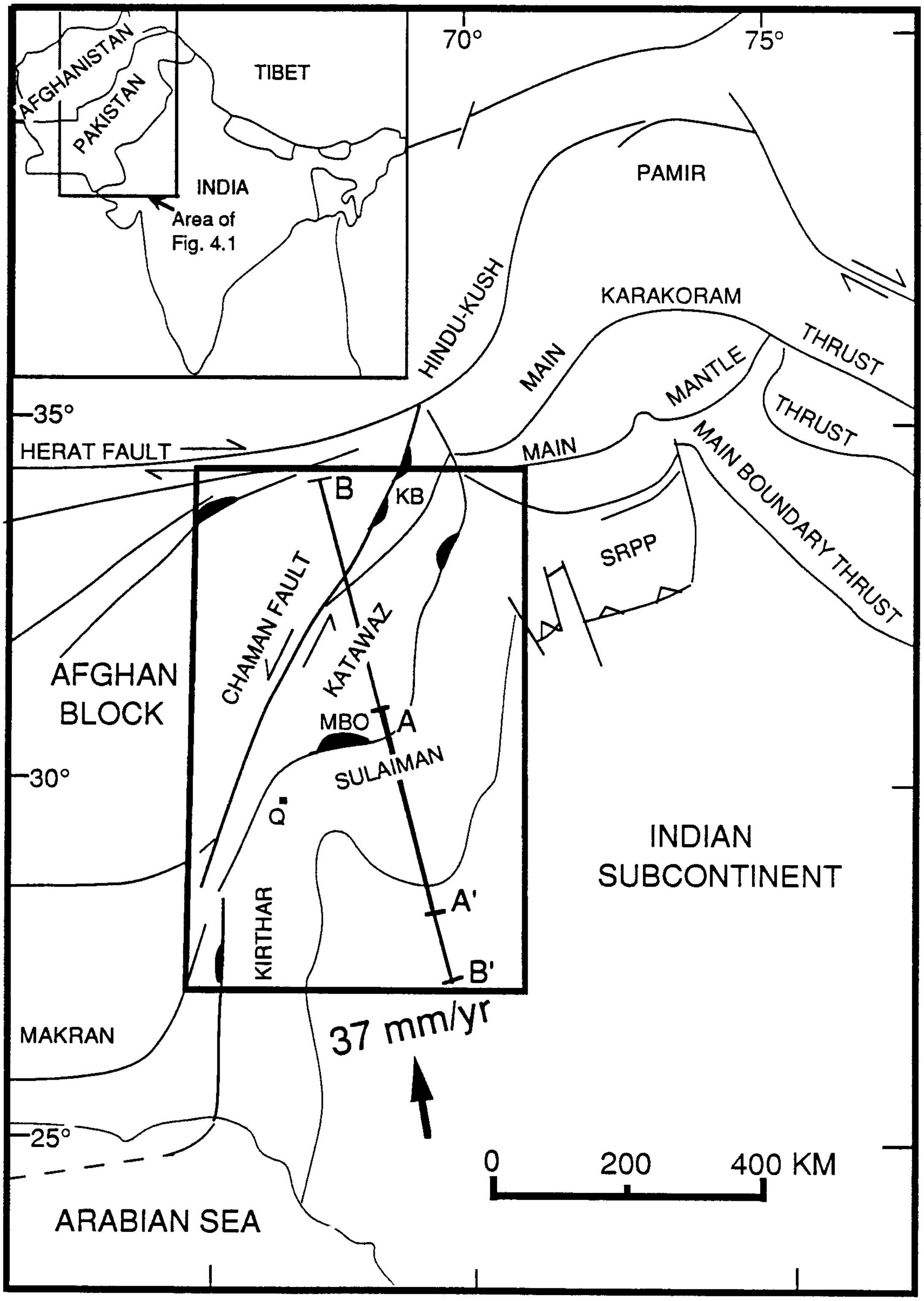
In this paper, surface geologic, Landsat, and Bouguer gravity data are integrated with seismic reflection profiles and borehole data to draw a structural and a crustal section across the entire Sulaiman fold belt to: 1) recognize geometry, structural style, and evolution of surface and deep structures in the Sulaiman fold belt; 2) evaluate shortening in the cover strata of the Indian subcontinent; 3) determine crustal variation underneath the Sulaiman fold belt and along the Indian/Afghan collision zone; and 4) reconstruct the pre-collisional passive margin of the Indian subcontinent.

TECTONIC FRAMEWORK AND STRATIGRAPHY

The foreland part of the main Himalayan mountain system in India is narrow and has steep topography that reflects effective decoupling at the base of the wedge (Jaume and Lillie, 1988). Typical of the foreland in Pakistan are two broad lobate features of gentler topography: the Salt Range/Potwar Plateau and the Sulaiman fold belt (Fig. 4.1). Sarwar and DeJong (1979) and Seeber (1981) interpreted these to be tear fault bounded features that are translated southwards along a weak decollement in Eocambrian salt. This interpretation is similar to that proposed for the foreland translation of the Pine Mountain thrust block of the Central Appalachians (Rich, 1934; Harris and Milici, 1977) and the Jura Mountains of Europe (Laubscher, 1981).

Direct collision in northern Pakistan gives way to transpression in the Sulaiman fold belt at the western edge of the Indian subcontinent (Sarwar and DeJong, 1979; Lawrence et al, 1981a; Klootwijk et al, 1981, 1985; Farah et al, 1984). Collisional processes started with emplacement of ophiolites in the Paleocene to Early Eocene (Allemann, 1979; Otsuki et al, 1989). This event is controlled by an extensive Paleocene/Cretaceous unconformity, onlap of Eocene strata, and age dating in north Pakistan (Hunting Survey Corporation, 1961; Allemann, 1979; Yeats and Hussain, 1987; Baig, 1990). Subsequently, Khojak flysch was deposited from early Eocene to Miocene (Lawrence and Khan, 1991a). Oblique subduction and rapid northwards motion of the Indian subcontinent initiated the major, left-lateral strike-slip Chaman fault system in Miocene time (Lawrence et al, 1981a; Lawrence and Khan, 1991b). The most western fault of this system, the Chaman fault, extends for 860 km, and has a displacement of 450±10 km (Lawrence and Khan, 1991b). This is evidenced by the displacement of Khojak flysch, offset of regional markers, and associated left-lateral shear. Simultaneous thrusting detached and displaced cover sediments of the Indian margin to the south and east. Renewed thrusting since the late Oligocene-early Miocene constantly reworked the molasse strata, migrating the Indus basin farther east and south (Banks and Warburton, 1986; Waheed et al, 1988; Ahmad and Khan, 1990). This motion is similar to the

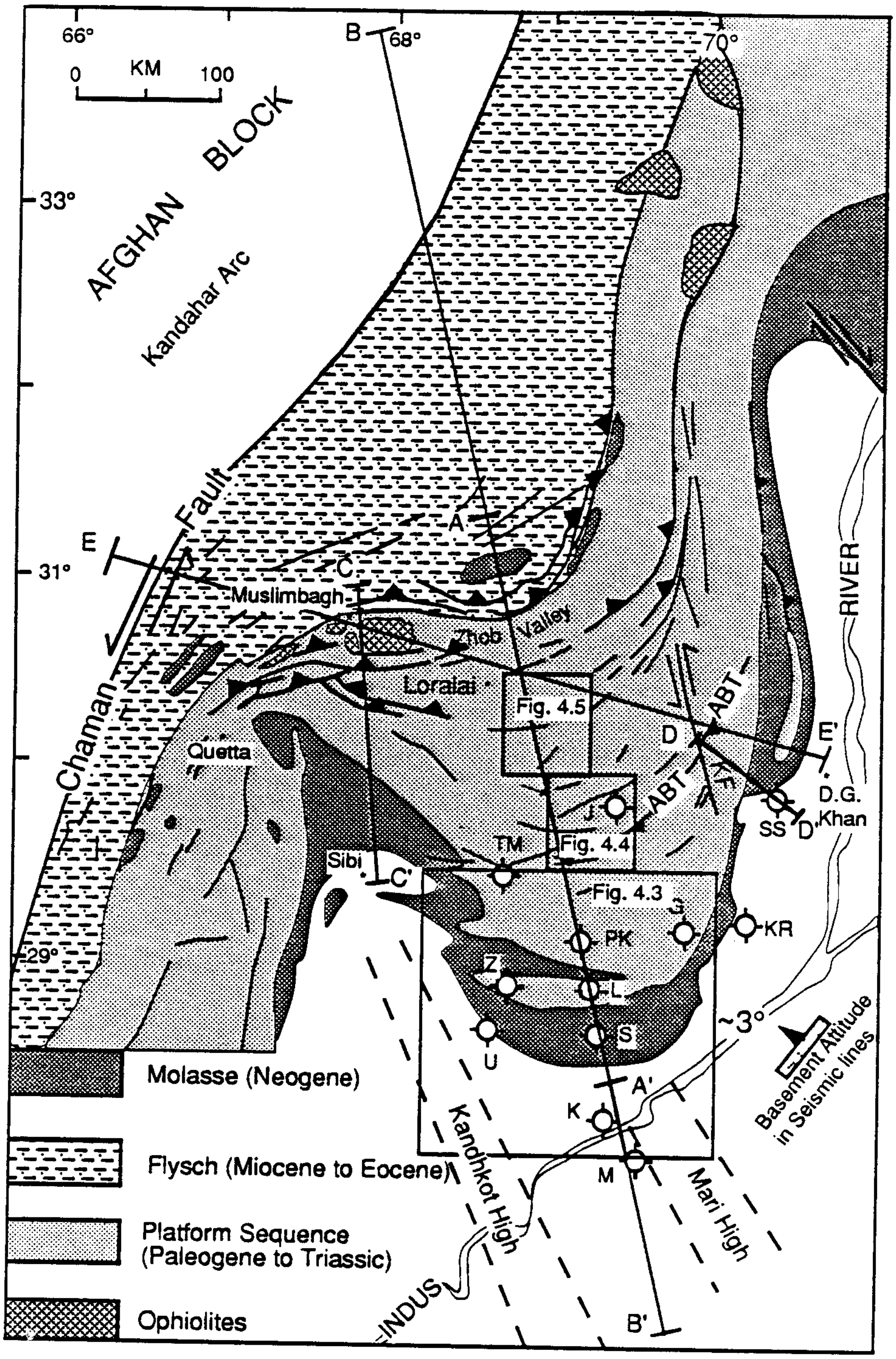
Figure 4.1. Simplified tectonic map of the Indian/Afghan collision zone. The large arrow shows convergence vector of India relative to the Afghan block while the one on the right shows India relative to Asia (Minster et al, 1974). Box shows the location of the figure 4.2. KB = Kabul Block, MBO = Muslimbagh Ophiolites, Q = Quetta, SR/PP=Salt Range/Potwar Plateau.



70°
75°
TIBET
AFGHANISTAN
PAKISTAN
INDIA
Area of
Fig. 4.1
PAMIR
KARAKORAM
THRUST
HINDU-KUSH
MAIN
MANTLE
THRUST
MAIN
MAIN BOUNDARY THRUST
35°
HERAT FAULT
B
KB
SRPP
CHAMAN FAULT
KATAWAZ
AFGHAN
BLOCK
MBO
A
SULAIMAN
30°
Q
INDIAN
SUBCONTINENT
A'
KIRTHAR
B'
MAKRAN
37 mm/yr
25°
0
200
400 KM
ARABIAN SEA

Figure 4.1

Figure 4.2. Generalized tectonic map of the Sulaiman lobe (modified from Kazmi and Rana, 1982). Areas of Figs. 4.3, 4.4, and 4.5 are shown by boxes. Lines A-A' and B-B' show the locations of the balanced structural cross-section (Fig. 4.13) and Bouguer gravity profile (Fig. 4.15) respectively. C-C' and D-D' show the location of balanced cross-sections by Banks and Warburton (1986) and Humayon et al (1991) respectively. E-E' shows gravity profile by Khurshid (1991). Well abbreviations: G = Giandari-1, J = Jandran, K = Kandkot-2, KR = Kotrum, L = Loti-2, M = Mari-2, PK = Pirkoh-2, S = Sui-1, SS = Sakhi Sarwar, TM = Tadri Main, U = Uch, Z = Zin.



66°
68°
70°
B
B'
0 KM 100
AFGHAN BLOCK
Kandahar Arc
33°
31°
29°
Chaman Fault
E
E'
A
A'
C
C'
D
D'
Muslimbagh
Zhob Valley
Loralai
Quetta
Sibi
Fig. 4.5
Fig. 4.4
Fig. 4.3
ABT
KF
J
TM
SS
D.G. Khan
RIVER
G
PK
KR
Z
L
S
U
K
M
~3°
Basement Attitude in Seismic lines
Kandhkot High
Mari High
INDUS
Molasse (Neogene)
Flysch (Miocene to Eocene)
Platform Sequence (Paleogene to Triassic)
Ophiolites

Figure 4.2

southward migration of the active foredeep basins of the Ganges plain in India and Jhelum plain in Pakistan (Acharyya and Ray, 1982; Raiverman et al, 1983; Johnson et al, 1985). Generally, surface exposures contain progressively older rocks towards the hinterland of the Sulaiman fold belt. The units range from Neogene molasse strata in the foreland and foredeep region to Carboniferous/Triassic marine and slope facies overlain by ophiolites in the hinterland (Hunting Survey corporation, 1961; Kazmi and Rana, 1982).

The main structural elements in the Sulaiman fold belt are east-west trending folds and faults that rotate rapidly to a north-south direction along the margin of the fold belt (Fig. 4.2). The left-lateral active Kingri tear fault on the eastern side (Abdul-Gawad, 1971; Rowlands, 1978) and a newly recognized basement high below Ziarat along the western margin of the Sulaiman fold belt (Khurshid, 1991) may serve as lateral ramps. It is possible that the Ziarat basement high in the fold belt is an extension of the Kandhkot high (Fig. 4.2) that is recognized in the foredeep region (Hunting Survey Corporation, 1961; Auden, 1974; Quadri and Shuaib, 1986; Raza and et al, 1989). A right-lateral focal mechanism solution for the shallow, January 20, 1973, earthquake of magnitude 5.6 from the southwestern part of the Sulaiman fold belt (Quittmeyer et al, 1979, 1984) may be related to the interface between this basement high (lateral ramp) and southward-translating thrust sheets.

Two different structural models have been proposed for the evolution of the Sulaiman fold belt (Banks and Warburton, 1986; Bannert et al, 1989). Geological maps of the Hunting Survey Corporation (1961) and Kazmi and Raza (1982) show thrust faults exposed as imbricate structures in the central and northern part of the fold belt. Bannert et al (1989) interpret these faults as foreland-verging thrusts. Banks and Warburton (1986) proposed a passive-roof duplex style of deformation from the Kirthar and western Sulaiman fold belts (C-C' in Fig. 4.2). A similar style of deformation is recognized from the frontal (Jadoon et al, 1991) and eastern (D-D' in Fig. 4.2; Humayon et al, 1991) parts of the Sulaiman fold belt. This paper is, in part, designed to test these models along a balanced cross-section (A-A' in Fig. 4.2) across all the Sulaiman fold belt.

S-wave studies of earthquake data (Chun, 1986) and Bouguer gravity modelling along transact E-E' (Khurshid, 1991) in Fig. 4.2 suggest crystalline oceanic/transitional crust underneath the Sulaiman fold belt. These results are tested in this study by Bouguer gravity modelling along crustal transect B-B' in Fig. 4.2.

DATA, GENERAL OBSERVATIONS, AND INTERPRETATIONS

Surface Geology and Landsat Data

Geological maps (1:50,000) by the Oil and Gas Development Corporation of Pakistan (OGDC) of the frontal folds, unpublished maps (1:250,000) in the Geological Survey of Pakistan (GSP) from the central Sulaiman (Mari-Bugti area), and the Hunting Survey Corporation maps (1:253,440) along with Landsat data (1:125,000), provide surface geology coverage (Figs. 4.3, 4.4 & 4.5). This data set is used to constrain a balanced structural cross-section across the western collisional boundary of the Indian Subcontinent (A-A' in Fig, 4.2). Field checks were done along the cross-section in two seasons during the fall of 1988 and winter of 1990.

Study of the geological maps shows simple to complex surface structures from foreland towards hinterland (Figs. 4.3, 4.4, & 4.5). This variation is related to the active evolution of the Sulaiman fold belt. The general stratigraphy based on the seismic reflection profiles from the southern Sulaiman front (Fig. 4.6) is shown in Fig. 4.7.

Main Structural Zones of Sulaiman Lobe

For simplicity of discussion in this paper, the Sulaiman fold belt is divided into different structural zones along a regional, 349 km long balanced cross-section (A-A' in Fig. 4.2).

Southern zone. Southern Sulaiman fold belt consists of an area from the Sulaiman foredeep to Tadri and Sian Koh anticlines (Fig. 4.3). This area mainly consists of Tertiary molasse and Paleogene to Cretaceous platform sedimentary rocks. It is dominated by broad, east-west trending, doubly plunging surface folds whose axes rotate toward north-south at the edges of the fold belt.

Central zone. Central Sulaiman fold belt consists of an area between Tadri and Kohlu synclines (Fig. 4.4). This area is dominated by foreland and hinterland verging faults. These thrust/reverse faults juxtapose Cretaceous against Eocene rocks. Folds in the central zone appear to be related to these faults.

Northern zone. Northern Sulaiman fold belt consists of an area between Kohlu syncline to Muslimbagh (Zhob valley) ophiolites Fig. 4.2, 4.4, & 4.5). The exposed rocks are progressively older (Paleogene to Triassic) towards the north (Fig. 4.5). South of the Loralai valley, structures are dominated by symmetrical folds (wavelength about 10 km), e.g. the Garhar Ghar anticline (Fig. 4.5). These folds become much tighter

Figure 4.3. Geological map of the southern Sulaiman fold belt. Mapping is compiled from the unpublished maps of the Oil and Gas Development Corporation (OGDC), the Geological Survey of Pakistan (GSP), the Hunting Survey Corporation (1961), and from Landsat images (1:125,000) supplied by Earth Satellite Corporation. See Fig. 4.6 for available seismic reflection coverage. Dashed line shows the location of a part of the deformed and retrodeformed cross-section (A-A' in Figs. 4.2 & 4.13). Plate convergence vector of India relative to Afghan block is from Minster et al (1974).

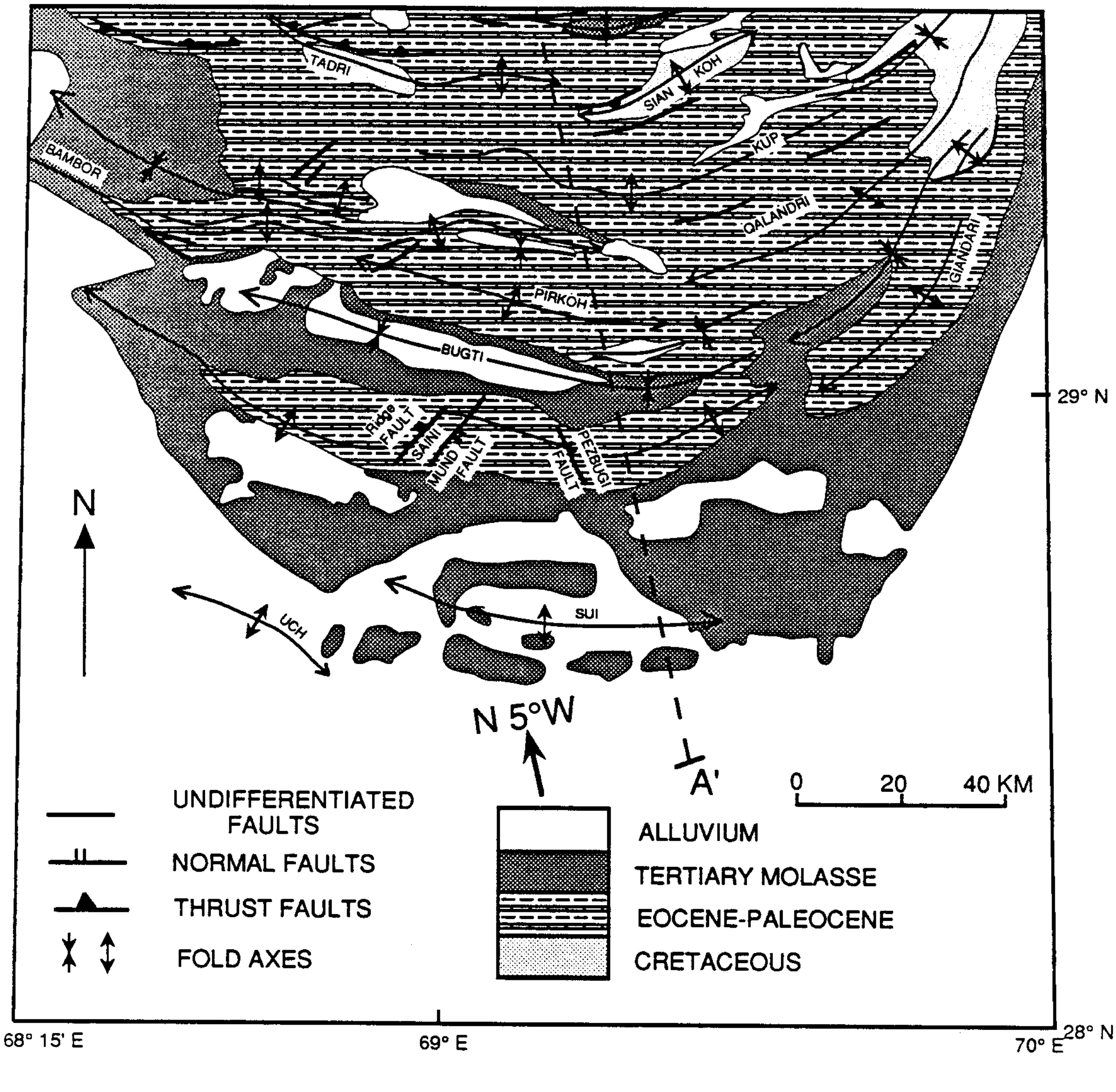

TADRI
SIAN KOH
KUP
BAMBOR
QALANDRI
GIANDARI
PIRKOH
BUGTI
Ridge FAULT
SAINI
MUND FAULT
PEZBUGI FAULT
29° N
N
UCH
SUI
N 5°W
A'
0
20
40 KM
UNDIFFERENTIATED FAULTS
NORMAL FAULTS
THRUST FAULTS
FOLD AXES
ALLUVIUM
TERTIARY MOLASSE
EOCENE-PALEOCENE
CRETACEOUS
68° 15' E
69° E
70° E
28° N

Figure 4.3

Figure 4.4. Geological map of the central Sulaiman fold belt. Compare the surface (secondary) structures in this map to the deep (duplex) structures in Figs. 4.10 and 4.12. Bold line shows the location of a part of the structural cross-section A-A' in Fig. 4.2.

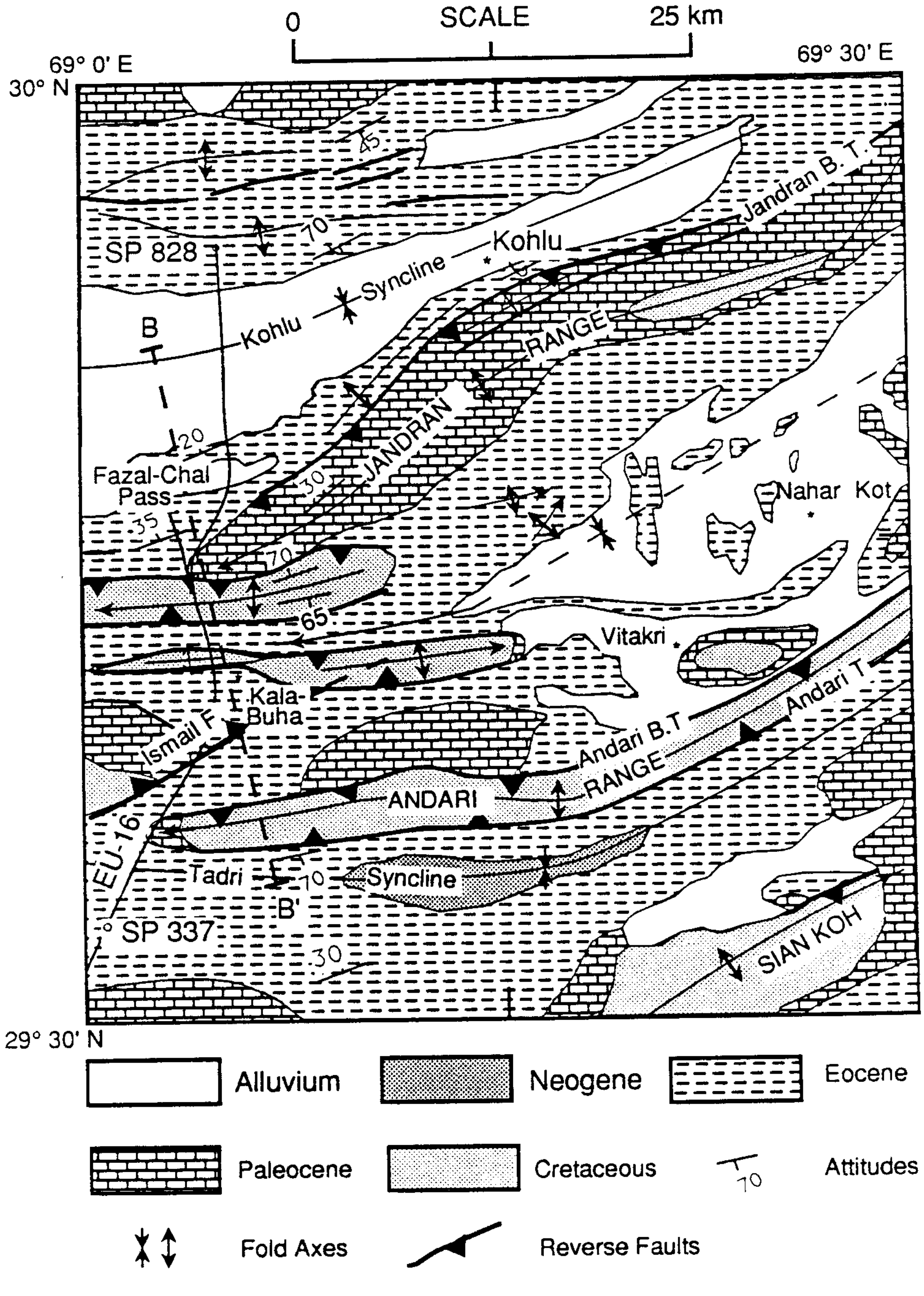

0
SCALE
25 km
69° 0' E
69° 30' E
30° N
29° 30' N
SP 828
Kohlu
Syncline
Kohlu
Jandran B. T.
RANGE
JANDRAN
B
Fazal-Chal
Pass
Nahar Kot
Vitakri
Kala-
Buha
Ismail F.
Andari B.T
Andari T.
RANGE
ANDARI
EU-16
Tadri
Syncline
B'
SP 337
SIAN KOH
Alluvium
Neogene
Eocene
Paleocene
Cretaceous
Attitudes
Fold Axes
Reverse Faults

Figure 4.4

Figure 4.5. Geological map of the northern Sulaiman fold belt (modified from Hunting Survey Corporation, 1961). See figure 4.2 for location. Notice the consistent uplift of the older rocks toward the north, widespread Cretaceous rocks, and the hot springs in the broad Loralai valley.

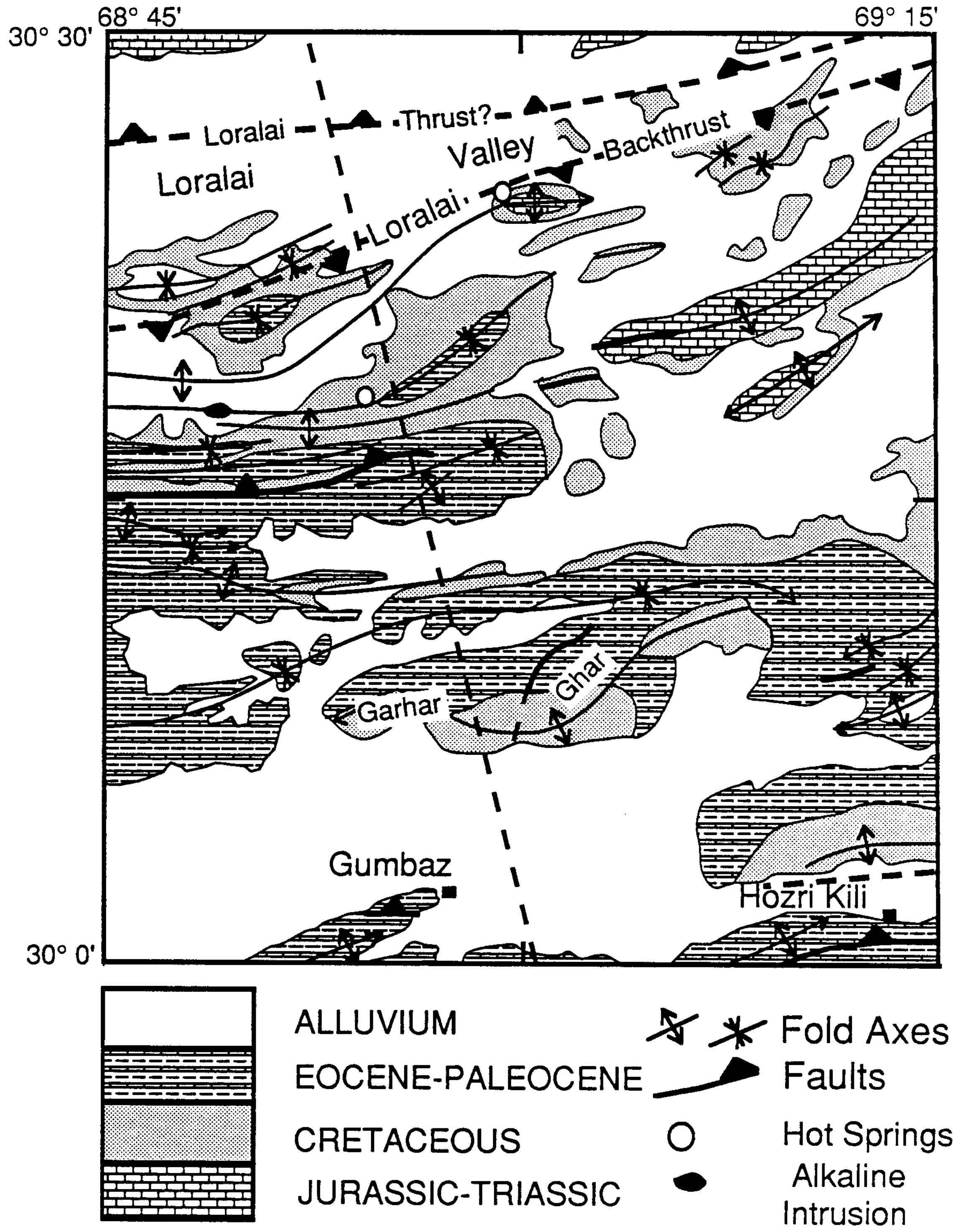

68° 45'
69° 15'
30° 30'
30° 0'
Loralai Thrust?
Loralai Valley
Loralai
Loralai Backthrust
Garhar
Ghar
Gumbaz
Hozri Kili
ALLUVIUM
EOCENE-PALEOCENE
CRETACEOUS
JURASSIC-TRIASSIC
Fold Axes
Faults
Hot Springs
Alkaline Intrusion

Figure 4.5

(wavelength less than 2 km) as the Loralai valley is approached (see maps of Hunting Survey Corporation, 1961). These tight folds may be interpreted as detachment folds with a decollement in thick Cretaceous shale that is extensively distributed in the Loralai valley.

Faults are present in the northern zone but are not as abundant as in the central zone. Two main faults are inferred in the Loralai valley (Fig. 4.5) based on an abrupt facies change and structural interpretation along the balanced structural cross-section. One fault, the Loralai thrust, is inferred due to distal pelitic facies of Jurassic limestone against shallow water massive limestone of the same age. Structures in the dominantly pelitic sequence are kink and box folds. The other fault,the Loralai backthrust, is based on the structural interpretation to be discussed below.

Other features of interest from the Loralai valley (Fig. 4.5) are two hot springs and the only pluton (a stock) recognized in this study. This stock (Tor Ghar) has a limited areal extent with diameter of a few hundred meters and height of about 175 meters from the ground level. A narrow zone of hornfelsed Cretaceous Sember shale immediately surrounds the pluton which sits in the center of an alluvial valley. This indicates that the maximum age of the pluton is late Cretaceous. However, the pluton preserves a chilled basic margin and a non-linear fabric suggesting it may be much younger in age. Petrography with nepheline, alkali feldspar, and phlogopite and pyroxene (cpx), olivine (forsterite), apatite, and sphene as minor minerals suggests this holocrystalline, silica-deficient rock is ijolite. In addition to this pluton, "volcanoes" are reported from the central zone (Bannert et al, 1989; S. H. Khan, personnel communication) based on Landsat data. Tor Ghar looks similar to a volcano from a distance and on imagery. I suggest that the "volcanoes" in the central zone may be stocks similar to the Tor Ghar. Such rocks are suggested to crystallize at shallow depth in provinces of alkaline volcanism (Hall, 1987). This is the first field report of the existence of anomalous alkaline rocks in the Sulaiman fold belt and is intended to attract the interested reader. Geochemical and age data on these rocks are important to understand their significance and role in this active convergent system.

Zhob (Muslimbagh) ophiolite zone. The northern zone is overlain by Zhob (Muslimbagh) ophiolites. These ophiolites composed of pillow basalts, sheeted dykes represent pieces of oceanic crust (Asrarullah et al, 1979; Abbas and Ahmad, 1979; Gansser, 1979; Farah and Zaigham, 1979), tectonically emplaced on the Sulaiman passive margin shelf and platform sequence during the Paleocene to Eocene (Allemann, 1979; Otsuki et al, 1989).

Khojak flysch zone. Khojak flysch represents a deep-water submarine clastic sediment fan. This fan, probably analogous to the present day Indus fan, was deposited on the oceanic crust mostly during Eocene to Oligocene in response to the first deformation episode of Himalayan orogeny (Lawrence and Khan, 1991a). Subsequently most of the deformation of the Khojak flysch occurred in the Oligocene to Miocene, as evidenced by an increase in sea-floor spreading velocities about 30 Ma (Lawrence and Khan, 1991a). Presently, it is found in the Makran Ranges and between the Chaman fault and shelf sediments of the Indo-Pakistan plate. Ophiolites are present along both sides of the Khojak flysch. To the south and east are the well known ophiolites of Waziristan, Muslimbagh, and Las-Bela (Asrarullah, 1979; DeJong and Subhani,1979; Otsuki et al, 1989). To the north and west, ophiolites are scattered along the Chaman fault, in the Ras Koh (Hunting Survey Corporation, 1961), and in the Kabul block (Lawrence and Khan, 1991a). Fragments of ophiolites along the Chaman fault were probably emplaced during the late Cretaceous/Paleocene contemporary with the Kandahar andesitic arc (Lawrence et al, 1981b; Debon et al, 1986).

Seismicity

The active nature of the Sulaiman fold belt is manifested by the multiple unconformities in continental molasse strata from the southern Sulaiman front (Tainish and Azad, 1959); magnetostratigraphy from the eastern Sulaiman Range (Ahmad and Khan, 1991), seismicity (Quittmeyer et al, 1979; 1984), and active faulting (Kazmi, 1979). Quittmeyer et al (1979) show many moderate to large earthquakes of magnitude 4 to 8. Recorded seismicity from 1915 to 1975 occurs as two distinct, linear, convex to the south, bands (Quittmeyer et al, 1979). The southern band occurs in the southern zone where only folds are exposed at the surface. This activity closely follows a topographic front along the Pirkoh fault-related anticline (Jadoon et al, 1991; Fig. 4.3). Thus southern band of activity is probably related to blind thrust faults in the southern zone.

The northern band of activity is associated with the exposed surface faults in the central Sulaiman fold belt (Quittmeyer et al, 1979; Fig. 4.4). It is not known whether all of these faults are active or, alternatively, the seismicity is related to a single, continuous fault (Quittmeyer et al, 1979). Four moderate to large earthquakes from the central Sulaiman fold belt were analyzed for focal depth and mechanism by Quittmeyer et al (1984). All of these events have been interpreted as shallow, less than 15 km depth with thrust solutions. The northern zone as well as the Zhob valley and Khojak Flysch is presently aseismic.

Figure 4.6. Map of seismic and well data coverage. A composite seismic line is shown in Fig. 4.10. Bold lines were used to project subsurface data onto the balanced cross-section A-A' (Fig. 4.11). The crystalline basement can be seen on seismic lines 834-SAJ-22 and W-15-BP. Well abbreviations are same as in Fig. 4.2. Data was released by Oil and Gas Development Corporation of Pakistan (OGDC), Amoco, and Texaco overseas.

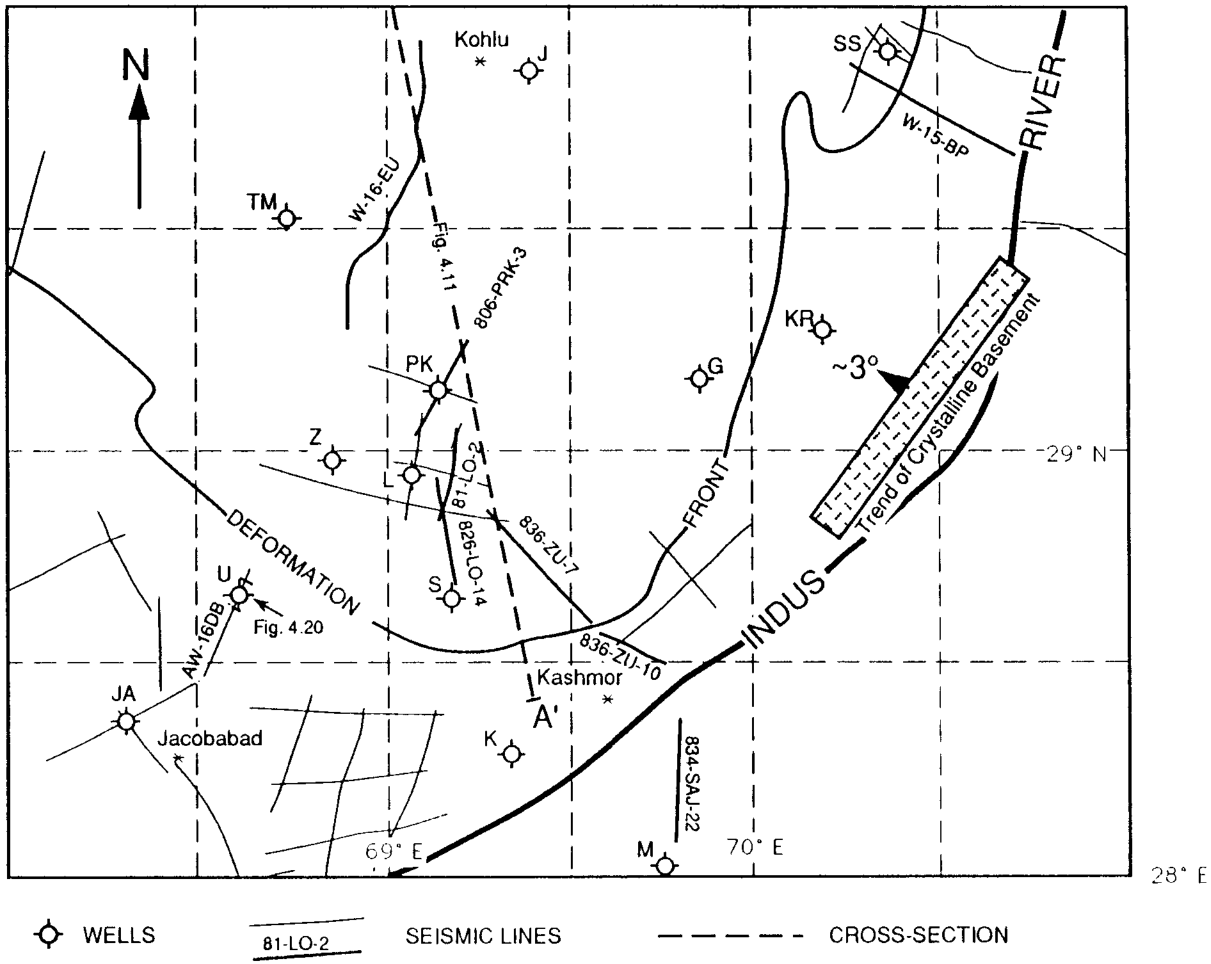

N
Kohlu
J
SS
W-15-BP
RIVER
TM
W-16-EU
Fig. 4.11
806-PRK-3
KR
G
~3°
Trend of Crystalline Basement
PK
Z
L
81-LO-2
29° N
836-ZU-7
826-LO-14
FRONT
DEFORMATION
U
S
INDUS
Fig. 4.20
AW-16DB
836-ZU-10
JA
Kashmor
A'
Jacobabad
K
834-SAJ-22
69° E
M
70° E
28° E
WELLS
81-LO-2
SEISMIC LINES
CROSS-SECTION

Figure 4.6

Figure 4.7. Simplified stratigraphic column of frontal Sulaiman fold belt. Approximate seismic velocities are estimates based on thicknesses from the well data, sonic logs, and converting stacking velocities from seismic lines to interval velocities. Tectonostratigraphic units are separated by floor and a roof thrusts.

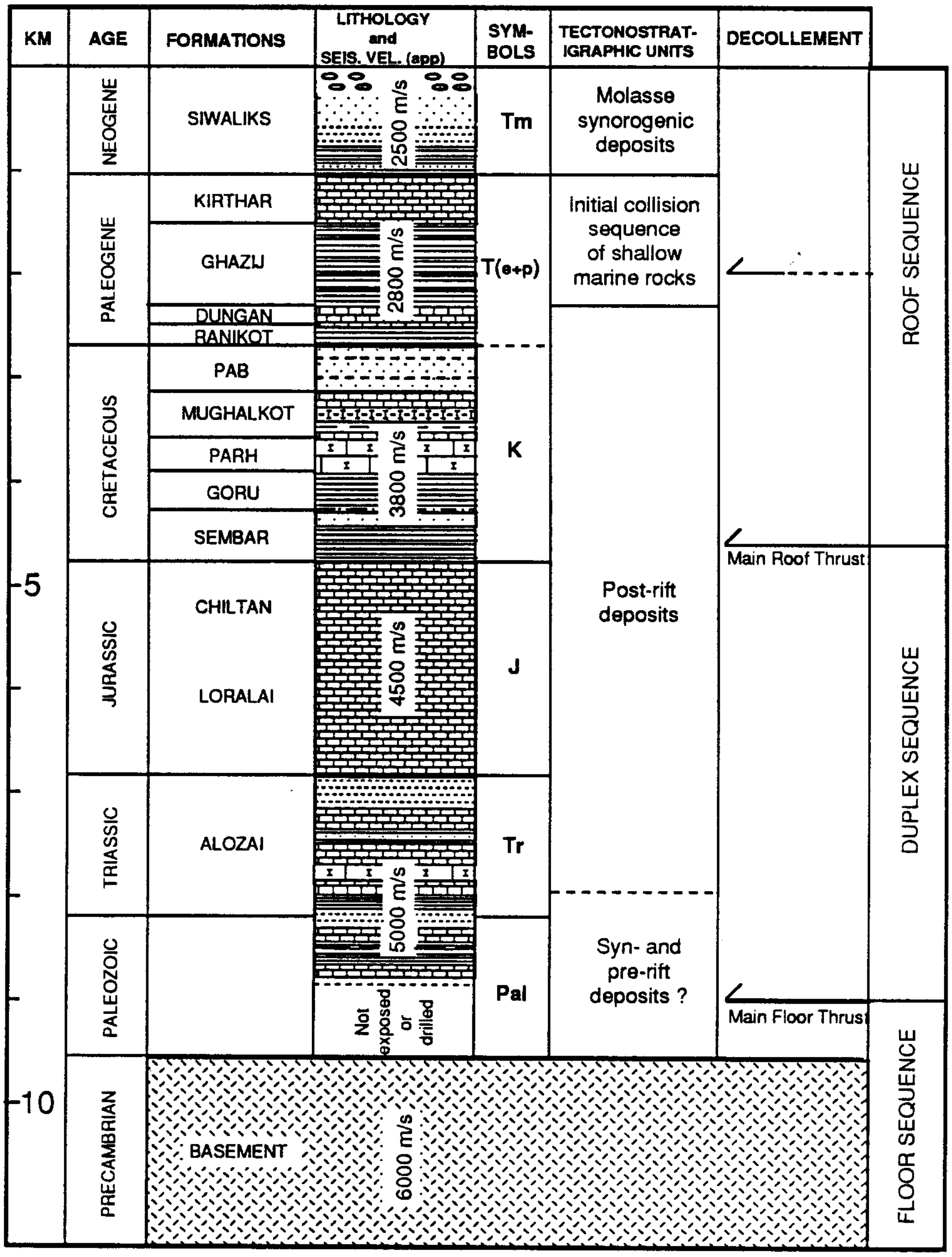

KM
AGE
FORMATIONS
LITHOLOGY and SEIS. VEL. (app)
SYM-BOLS
TECTONOSTRAT-IGRAPHIC UNITS
DECOLLEMENT
NEOGENE
SIWALIKS
2500 m/s
Tm
Molasse synorogenic deposits
PALEOGENE
KIRTHAR
GHAZIJ
DUNGAN
RANIKOT
2800 m/s
T(e+p)
Initial collision sequence of shallow marine rocks
CRETACEOUS
PAB
MUGHALKOT
PARH
GORU
SEMBAR
3800 m/s
K
Main Roof Thrust
ROOF SEQUENCE
5
JURASSIC
CHILTAN
LORALAI
4500 m/s
J
Post-rift deposits
DUPLEX SEQUENCE
TRIASSIC
ALOZAI
Tr
5000 m/s
PALEOZOIC
Not exposed or drilled
Pal
Syn- and pre-rift deposits ?
Main Floor Thrust
10
PRECAMBRIAN
BASEMENT
6000 m/s
FLOOR SEQUENCE

Figure 4.7

Figure 4.8. Geothermal gradient in the boreholes from the Sulaiman fold belt (data from Khan and Raza, 1986; Raza et al, 1989a). Strength of the rocks decreases with increasing pressure and temperature below the brittle/ductile transition (Davis and Engelder, 1985). Average geothermal gradient of about 30°C/km suggests that at depths of 8-10 km carbonates are as weak as salt at a very shallow depth . Well abbreviations are the same as in Fig. 4.2.

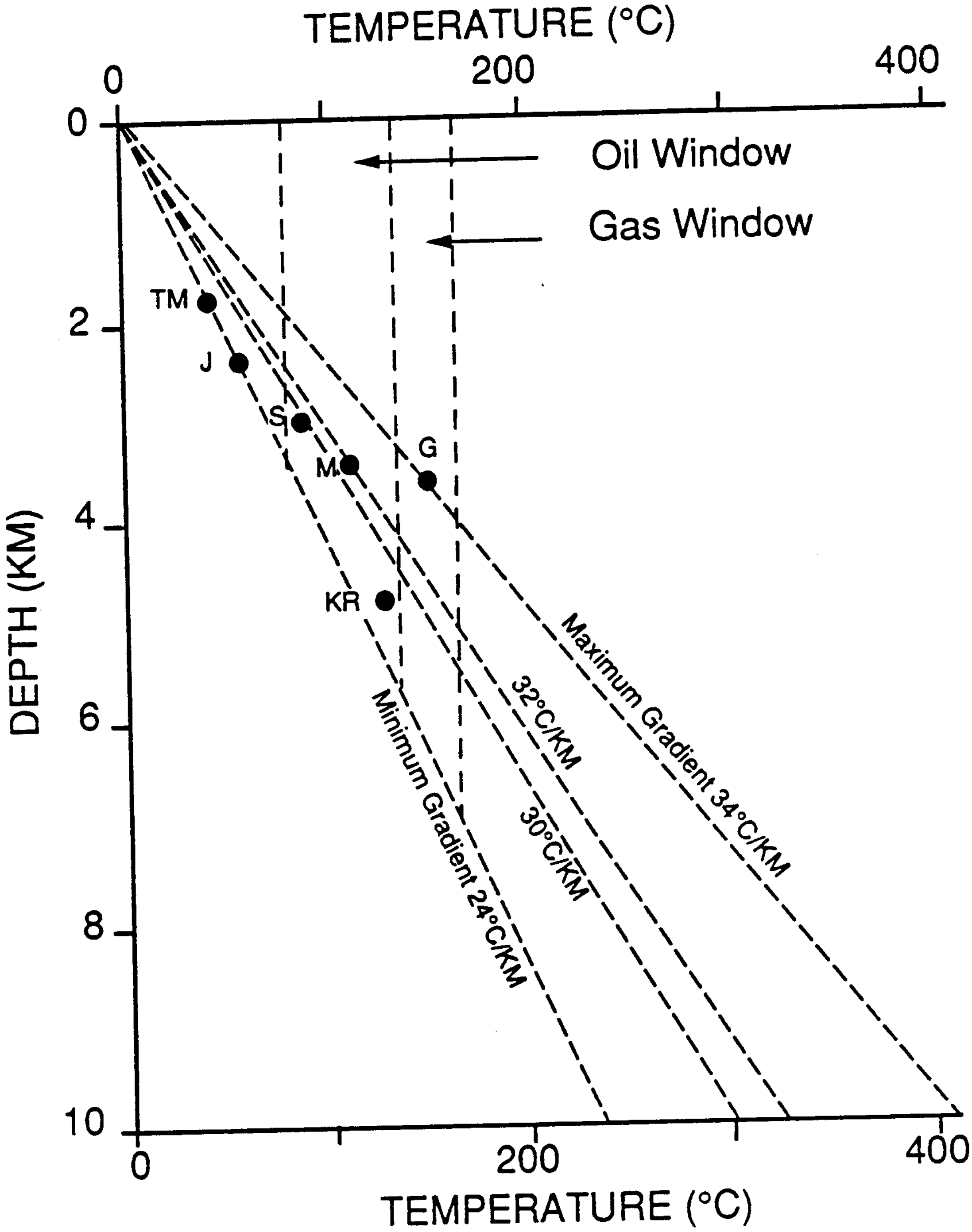

TEMPERATURE (°C)
0
200
400
0
2
4
6
8
10
DEPTH (KM)
Oil Window
Gas Window
TM
J
S
M
G
KR
Maximum Gradient 34°C/KM
32°C/KM
30°C/KM
Minimum Gradient 24°C/KM
0
200
400
TEMPERATURE (°C)

Figure 4.8

Seismic Reflection Profiles and Boreholes

Extensive seismic reflection and borehole data from the frontal part of the Sulaiman fold belt and the adjacent foredeep (Fig. 4.6) have been provided to Oregon State University by the Oil and Gas Development Corporation of Pakistan (OGDC), the Hydrocarbon Development Institute of Pakistan (HDIP), Amoco and Texaco oil companies. These data provide good seismic coverage from the southern Sulaiman foredeep and extends about 160 km to the north into the fold-and-thrust belt from the deformation front.

Seismic data are used to resolve: (a) the major decollement; (b) trend and depth to the top of the crystalline basement to constrain stratigraphic and tectonic thicknesses and Bouguer gravity modelling; and (3) the geometry of structures along balanced structural cross-section A-A' in figure 4.2. The first two constraints are vital to resolve the geometry of structures and style of deformation. ,

Depth and nature of major decollement

Surface geology (Hunting Survey Corporation, 1961; Fig. 4.3, 4.4, & 4.5) suggests that progressively younger rocks are exposed towards the foreland in the Sulaiman lobe. Stratigraphy based on seismic reflection and borehole data shows an about 10 km thick undeformed sequence of rocks at the Sulaiman mountain front (Fig. 4.7). The stratigraphic column suggests potential decollement horizons in Eocene, Cretaceous, and in Paleozoic rocks. At the beginning of this study, it seemed possible that a hinterland decollement surface in Paleozoic section gradually steps up to the Cretaceous and Eocene in the foreland. However, seismic reflection profiles show that all the stratigraphic section is detached from the basement in the southernmost Sui and Loti anticlines (81-LO-14, 81-LO-2 in Figs. 4.6). Thus, the major decollement remains in Paleozoic rocks at the interface between crystalline basement and the sedimentary package at the deformation front (Fig. 4.7).

The gross geometry of the overthrust wedge, including gentle topography (<1°) and broad width (> 300 km), is compatible with that proposed by Davis and Engelder (1985) for thrust belts developed over a weak decollement. A thin-skinned style of deformation is supported by the seismic reflection data from the Sulaiman fold belt (Humayon et al, 1991; Jadoon et al, 1991). However, there is evidence that the Eocambrian evaporite sequence that provides an effective zone of decoupling at the base of the section in the Salt Range and Potwar Plateau (Lillie et al, 1987; Jaume and Lillie, 1988;

Pennock et al, 1989) may not be present underneath the Sulaiman fold belt. This evidence includes: (a) absence of salt related diapiric structures (e.g., tight anticlines, broad synclines and disharmonic folding); (b) the closest observation of the Eocambrian evaporites in wells and seismic lines is about 200 km east of the deformation front (Humayon et al, 1991); and (c) the signature of the ductile zone (salt pillows) associated with the evaporites drilled in wells dies out westward before reaching the Sulaiman front. Evaporites have not been seen in the seismic lines from the southern Sulaiman foredeep (Jadoon et al, 1991). Unlike the 2 to 4 km depths in the frontal Salt Range/Potwar Plateau, seismic reflection data from the Sulaiman fold belt show that the decollement is about 10 km deep at the base of the wedge at the deformation front (81-LO-2 in Fig. 4.6). Khan and Raza (1986) and Raza et al (1989a) calculate an average geothermal gradient of about 30°C/km in boreholes from the Sulaiman foreland and adjacent foredeep (Fig. 4.8). Davis and Engelder (1985) show that with a geothermal gradient such as this, limestones at depths of about 10-12 km are as weak as evaporites. This suggests that the effective zone of weak decoupling in the Sulaiman may be in fine-grained carbonate rocks at depths of 10-15 km (Lillie and Davis, 1990). The stratigraphic section suggests abundant pelitic rocks at this level which also might provide a weak zone through dewatering and/or recrystallization. Thus at this depth fine-grained sedimentary rocks may provide a weak detachment similar to the evaporites at depths of 1 to 3 km beneath the Salt Range/Potwar Plateau region.

Crystalline basement and sedimentary package

It is important to locate the top of crystalline basement in a fold-and-thrust belt in order to evaluate: 1) total thickness (stratigraphic and tectonic) of the sedimentary wedge above the basement; 2) location and nature of the decollement at the base of the wedge or in some younger horizon: 3) basement slope, which is important in understanding the mechanics of thrusting (Davis et al, 1983; Davis and Engelder, 1985; Jaume and Lillie, 1988); and 4) the role of basement structures in controlling the deformation (Jackson, 1980; Baker et al, 1988).

Most seismic reflection lines in figure 4.6 include data of 5 seconds on 2 way travel time. Due to the extreme thickness of the sediments, basement can only be seen on lines W-15-BP from the eastern, and SAJ-22 from the southern, foredeep. Seismic reflection data (SAJ-22 in Fig. 4.6) show that the Precambrian to Quaternary rocks are about 6 km thick in the foredeep near the Mari gas fields and that they thicken stratigraphically to about 8 km along the axis of the Indus river (Jadoon et al, 1991). At the deformation front, the basement reaches depths beyond 5 seconds two-way travel time. However, the basement configuration is interpreted extrapolating the layercake stratigraphy into the thrust belt from the foredeep region (bold lines in Fig. 4.6). The seismic reflection data show a stratigraphic thickness of about 10 km at the deformation front of the Sulaiman fold belt (Fig. 4.7). Extrapolating the top of basement dip (2°-2.5°) to the north suggests a tectonic thickness of about 20 km in the hinterland. Planar stratigraphy and broad structures as far north as Bugti syncline suggest a planar basement surface. However, the presence of rift-related features is not precluded because a thin, extended crust is interpreted underneath the Sulaiman fold belt (Khurshid, 1991; discussion below).

BALANCED STRUCTURAL CROSS-SECTION

Section Balancing

Line length and area balancing techniques (Bally et al, 1966; Dahlstrom, 1969a; Gwinn, 1970; Elliot, 1982; Woodward et al, 1989) were applied to the cross-section (A-A' in Figs. 4.2, 4.11, & 4.13). The southern 159 km long part of the cross-section is thoroughly constrained by seismic reflection and well data (Fig. 4.6, 4.9, & 4.10) and was balanced by the line-length method except under the frontal broad folds (Sui and Loti). This technique is considered here to be invalid due to the ductility of material in the core zones of these anticlines. The northern 185 km of the cross-section north of kilometer mark 159 is primarily area-balanced (Fig. 4.13), due to lack of seismic data.

Surface and Subsurface Expression

Discussion along 349 km long balanced structural cross-section (A-A' in Fig. 4.2, 4.11, & 4.13) is divided according to the structural zones described earlier.

Sulaiman foredeep and the southern zone

Seismic reflection lines (Fig. 4.6) and borehole data (Fig. 4.9) provide sufficient subsurface data to constrain the Sulaiman foredeep and the southern zone. One of the most important observations resulting from the study of the composite seismic line (bold lines, Fig. 4.6) from the Mari well (line 834-SAJ-22) in the Sulaiman foredeep to Kohlu (line W-16-EU) in the central Sulaiman is the interpreted depth to the top of the crystalline basement. Seismic data suggest that depth to the top of crystalline basement is about 10 km at the deformation front. The basement descends northwards with a gentle inclination of about 2°-2.5° and attains a depth of about 15 km below Kohlu in the central zone.

The Sulaiman fold belt exposes Neogene molasse at the deformation front; a maximum of 2400 m thickness is encountered in the southern Sulaiman foredeep (Jadoon et al, 1991). Based on seismic data, Banks and Warburton (1986) reported about 7000 m of molasse sediments from the Sibi trough which is a deformation front of the western Sulaiman fold belt. Boreholes and the composite seismic reflection line show that unlike the platform sequence, the molasse strata reach maximum thickness in the foredeep and thin toward both the foreland and hinterland (Fig. 4.9 & 4.10).

Pre-molasse platform sediments thicken toward the hinterland (4.9 & 4.11). In the southern zone, progressively older rocks are exposed in the core zones of doubly plunging anticlines (e.g., the Sui anticline has molasse, the Loti, Pirkoh, Danda have Eocene strata while farther north the Kurdan and Tadri anticlines are cored by Paleocene and Cretaceous strata). These exposed rocks everywhere show a coherent stratigraphy as far north as Tadri syncline, and are not disrupted by significant thrust faults (Fig. 4.3). Boreholes in the frontal and central Sulaiman Range (Tadri and Jandran) penetrated a normal stratigraphic sequence as deep as Jurassic (Fig. 4.9). These observations collectively imply that towards the hinterland rocks are structurally uplifted from their regional stratigraphic level by duplication along blind thrusts below the Cretaceous.

The surface and seismic expression of the frontal part of the Sulaiman fold belt is of two broad (half wavelength about 20 km), small amplitude (1-2 km) anticlines (Sui and Loti). Limb dips do not exceed 4° on Sui and 15° on Loti (Fig. 4.10). The surface expression of the third folded structure (Pirkoh) is of a foreland-dipping monocline with dips between 35°-75° (Fig. 4.10 & 4.11). This fold has almost flat strata (nodular Eocene limestone) along its hinge area for about 15 km. The northern limb, over a buried ramp, is concealed below an anticline, and gives the entire sturcture a box-like form. Seismic reflection data show a hole of about 4 km under the hinge zone of the Pirkoh fold. This hole is logically filled by a duplex horse of massive Jurassic (Chiltan) limestone and older rocks. This interpretation suggests that the Pirkoh structure is a duplex related, fault-bend fold. The flat ground along the hinge zone of the Pirkoh is due to the hanging wall flat of Pirkoh duplex horse over the footwall flat of the Loti fold. Banks and Warburton (1986) first suggested that the surface expression of duplex structures with a passive-roof sequence may be a foreland-dipping monocline. The steep foreland dipping limb of a monocline, like the Pirkoh structure, may represent a culmination wall over the foreland propagating duplexes. On the seismic reflection lines, Cretaceous and younger rocks are consistently uplifted in the core zones of anticlines, starting with the Bugti syncline at the tip of the Pirkoh fault-bend fold (Fig. 4.10). Structural relief of about 4 km below the Pirkoh structure increases to about 8 km below Tadri and about 10 km just south of the Loralai triangle zone (130 km north of the tip of Pirkoh). Stratigraphy is not disrupted by major faults above the Jurassic in the Sulaiman fold belt. This structural uplift is interpreted to be due to a thin-skinned, passive-roof duplex style of deformation (Figs. 4.10 & 4.11). The duplex sequence consists of Jurassic and older rocks, bounded between a floor thrust at the base of the wedge and a roof thrust (Dahlstrom, 1970) or upper detachment (Jones, 1982) in Cretaceous shales. The roof sequence is recognized to remain passive during the forward propagation of the underlying duplex horses. It is regarded as a passive-roof sequence with a decollement in thick Cretaceous shales.

The composite seismic reflection profile and balanced cross-section shows a continuous passive-roof sequence in the southern zone. The structures in it are fault-related folds of variable tightness, symmetry, and extent as a result of variable ramp spacing and relative displacement (hybrid folds of Mitra, 1986). These broad folds at the surface reflect the shape of deep structures associated with faults in the duplex sequence which never break the surface in this zone of blind faults.

Central zone

North of the Tadri syncline, complicated structures (Morley, 1988) appear at the surface (Fig. 4.4). These structures are foreland and hinterland verging reverse faults, and associated small wavelength, fault-bounded anticlines. Along these faults, mostly Cretaceous rocks juxtapose Eocene rocks. At the surface, these faults are of great lateral extent (10,s of km; Fig. 4.4). The Andari backthrust (Figs. 4.2 & 4.4) that emerges from the Tadri syncline with a backthrust sense of vergence alone extends for about 170 km (Figs. 4.2, & 4.4). Bannert et al (1989) suggest a foreland vergence along these faults, based on Landsat interpretations. They suggest that major shortening in the Sulaiman fold belt is along some of these faults. Humayon et al (1991) recognized the backthrust sense of vergence along the Andari fault in the eastern Sulaiman Ranges and interpreted it to emerge from the passive-backthrust. Critical observation of seismic data (Fig. 4.10) shows minor throw (1-2 km) mostly of top Cretaceous, Paleocene, and Eocene rocks along these faults (Figs. 4.10, 4.11, & 4.12). These observations suggest that the faults are secondary structures (out-of-sequence thrusts of Morley, 1988), mostly restricted to the passive-roof sequence. One exception is the Jandran backthrust that cuts through the upper duplex horse (M1). Tight, short wavelength anticlines associated with these faults are interpreted as pop-ups (Mari Pop-Up Zone) in the roof sequence (Figs. 4.4 & 4.12). Parry (1978) and Mitra (1987), and Ahmed and McElroy (1991) have shown similar structures in cross-sections from West Virginia and Kohat Plateau of the Trans-Indus Salt-Range respectively. Active shallow seismicity (about 5 km) in the central Sulaiman Range (Quittmeyer et al, 1979, 1984), tilted gravel beds, and landslides in the Mari pop-up zone suggest that some of these faults may be active. This interpretation suggests that north of the Tadri anticline, structures (tight) in the roof-sequence are different from the deep (relatively broad) structures in the duplex sequence.

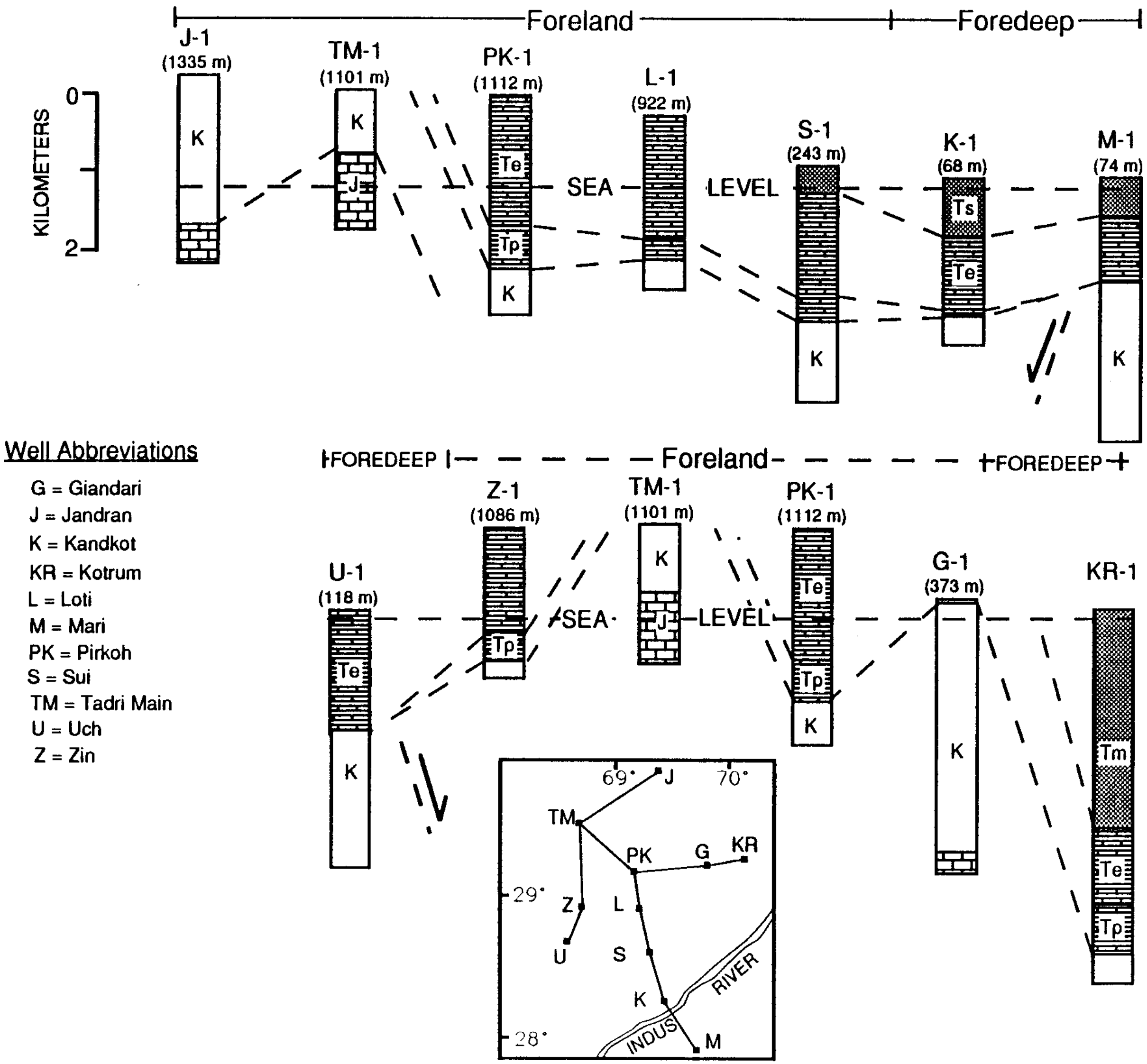
Although the passive-roof sequence is disrupted by reverse faults in the central zone, it is not emergent due to minor throw along these secondary faults (Fig. 4.12). These out-of-sequence reverse faults may represent an early stage in the development of one or more overstep backthrusts emerging from the passive-roof thrust. This suggests that multiple backthrusts which were proposed to serve as a mechanism for the shortening strain in the passive-roof sequence (Banks and Warburton, 1986) are not present or are only incipiently present at the current stage of central Sulaiman deformation.

Northern zone

Seismic data do not exist from the northern zone. Constraints and the problem for the structural interpretation of the northern zone are shown by Fig. 4.11. Basement and the decollement surface is extrapolated as it descends northwards from the central and southern zone. The structural profile (A-A' intersects an east-west Bouguer gravity profile (E-E') in the Loralai valley (Fig. 4.2). Crystalline basement along this Bouguer gravity profile (E-E' in Fig. 4.2) is extrapolated (Khurshid, 1991) by the seismic reflection data from the eastern Sulaiman foreland and associated foredeep (Humayon et al, 1991). About 18 km depth to the crystalline basement at the intersection of two profiles is consistent. Surface geology is mostly from Hunting Survey Corporation (1961) at a scale of 1:253,440 and Bhatti et al (1984) at a scale of 1:25,000 for the Gumbaz area in Fig. 4.5. Geology was field checked by the author where possible during the field season in fall of 1988 and winter of 1990. Plot of surface geology leaves a hole (problem in Fig. 4.11) of more than 10 km thickness below the Loralai and Zhob areas (Fig. 4.11). This hole is hypothetically filled by duplexes of Jurassic and older rocks analogous to those from the southern and central zones (Fig. 4.13).

Important structural elements of the northern zone are a structural depression (Gumbaz in Fig. 4.13), emergent passive-roof sequence in the Loralai valley along a

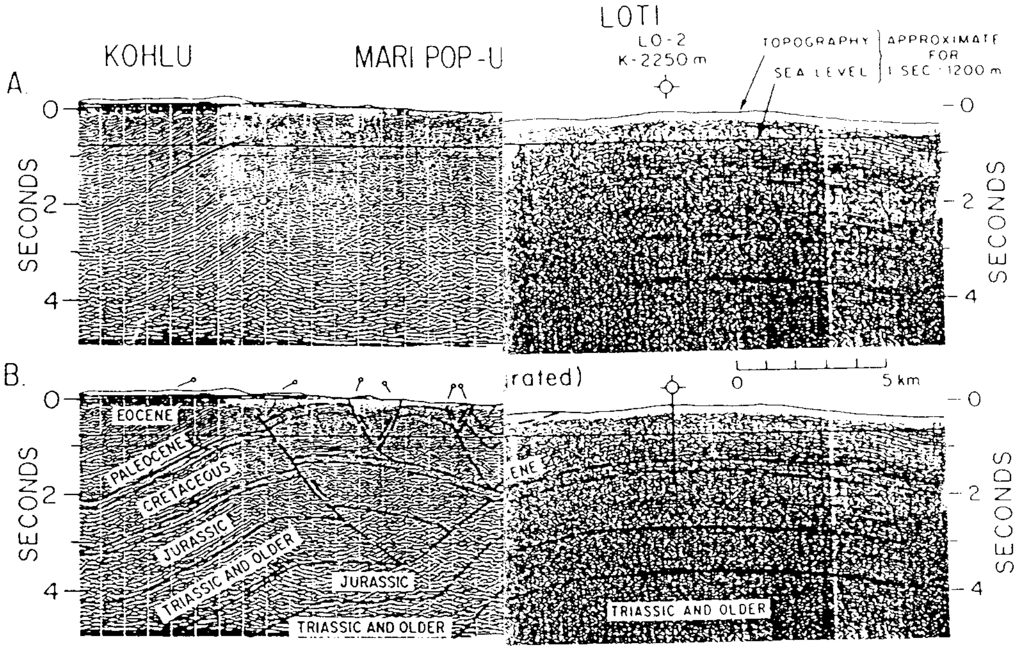
Figure 4.9. Well data from the Sulaiman foreland and adjacent foredeep. Notice tectonic uplift of rocks towards foreland, coherent stratigraphy, and stratigraphic thickeness variation of the platform and the Molasse strata.



Foreland
Foredeep
KILOMETERS
0
2
J-1
(1335 m)
TM-1
(1101 m)
PK-1
(1112 m)
L-1
(922 m)
S-1
(243 m)
K-1
(68 m)
M-1
(74 m)
K
J
Te
Tp
Ts
SEA
LEVEL
FOREDEEP
Foreland
FOREDEEP
U-1
(118 m)
Z-1
(1086 m)
TM-1
(1101 m)
PK-1
(1112 m)
G-1
(373 m)
KR-1
Tm
Well Abbreviations
G = Giandari
J = Jandran
K = Kandkot
KR = Kotrum
L = Loti
M = Mari
PK = Pirkoh
S = Sui
TM = Tadri Main
U = Uch
Z = Zin
69°
70°
29°
28°
TM
J
PK
G
KR
Z
L
U
S
K
M
INDUS
RIVER

Figure 4.9

Figure 4.10. Composite uninterpreted (A) and interpreted (B) seismic line from southern and central Sulaiman fold belt. Basement in each case is below 5 seconds 2-way travel time. The interpretation shows a passive-roof duplex structure bounded by a roof thrust in Cretaceous shales and a floor thrust at the base of the wedge. Tip of the decollement extends below the broad Loti and Sui anticlines (Fig. 4.11). These structures are interpreted as concentric, buckle folds formed primarily due to ductility of material at the detachment horizon. Line 81-LO-2 is migrated 24 fold, dynamite source, recorded and processed in 1981 by OGDC. Line 816-PRK-3 is migrated 24 fold, dynamite source, recorded by OGDC in December 1980 to January 1981 and processed by Geophysical Service. Line W-16-EU is migrated 10-40 Hz, Vibroseis source, recorded and processed by Western Geophysical Company in 1975. Lines are tied along strike. Data gap between 816-PRK-3 and W-16-EU is bridged by surface geology control. Horizontal scale for the lines differ.



LOTI
LO-2
K-2250 m
KOHLU
MARI POP-U
TOPOGRAPHY
SEA LEVEL
APPROXIMATE FOR 1 SEC = 1200 m
A.
B.
SECONDS
0
2
4
rated)
0
5 km
EOCENE
PALEOCENE
CRETACEOUS
JURASSIC
TRIASSIC AND OLDER
JURASSIC
TRIASSIC AND OLDER
ENE
TRIASSIC AND OLDER

Figure 4.10

Figure 4.11. Balanced structural cross-section of the southern and central Sulaiman fold belt. Seismic data are projected from positions of bold lines in Fig. 4.6, onto the cross-section line A-A' in Fig. 4.2. Composite seismic line is shown in Fig. 4.10. Folds in the passive-roof sequence from the southern zone are related to blind faults at depth. Structure of the central zone is highlighted in Fig. 4.12. Letters identifying individual horses in the duplex sequence are from the individual mountains and from the geographic domains. Problem area in the section represents the space that has to be filled by structural duplication of the Jurassic and older strata. From north to south these areas are Z = Zhob valley, L = Loralai valley, D = Duki Valley, M1 -M2 = Mari, T1-T2 = Tadri, K = Kurdan, D = Danda, P = Pirkoh, L = Loti (future horse).

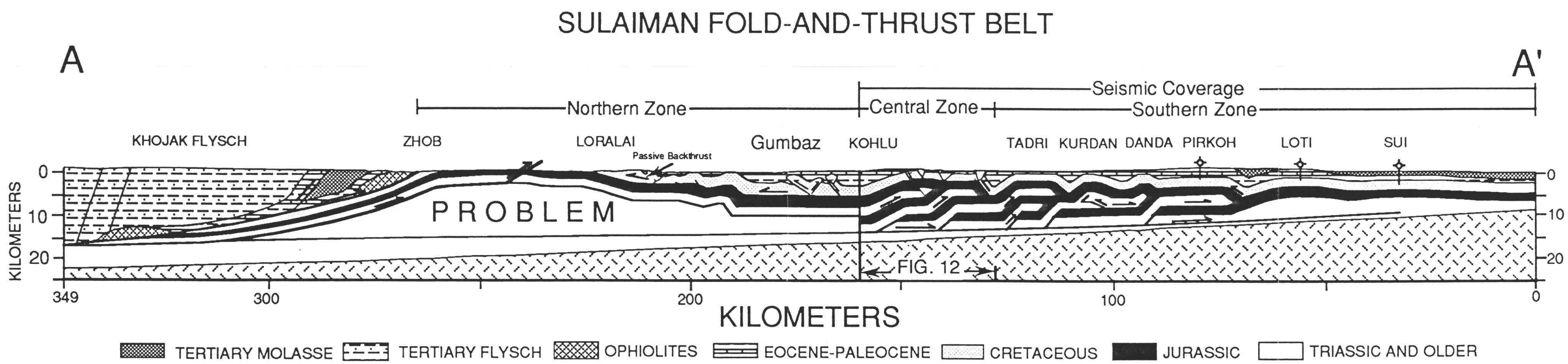

SULAIMAN FOLD-AND-THRUST BELT
A
A'
Seismic Coverage
Northern Zone
Central Zone
Southern Zone
KHOJAK FLYSCH
ZHOB
LORALAI
Passive Backthrust
Gumbaz
KOHLU
TADRI
KURDAN
DANDA
PIRKOH
LOTI
SUI
PROBLEM
KILOMETERS
0
10
20
FIG. 12
349
300
200
100
0
KILOMETERS
TERTIARY MOLASSE
TERTIARY FLYSCH
OPHIOLITES
EOCENE-PALEOCENE
CRETACEOUS
JURASSIC
TRIASSIC AND OLDER

Figure 4.11

Figure 4.12. Structural cross-section of the central Sulaiman fold belt. Notice pop-ups and associated reverse faults with minor throw of the top Cretaceous, Paleocene, and Eocene. These secondary faults emerging from the passive-roof thrust, may represent an early stage of development of overstep-backthrusts. Symbols along the profile shows the dip of exposed strata. See figure 4.11 for the patterns.

CENTRAL SULAIMAN
(MARI POP-UP ZONE)

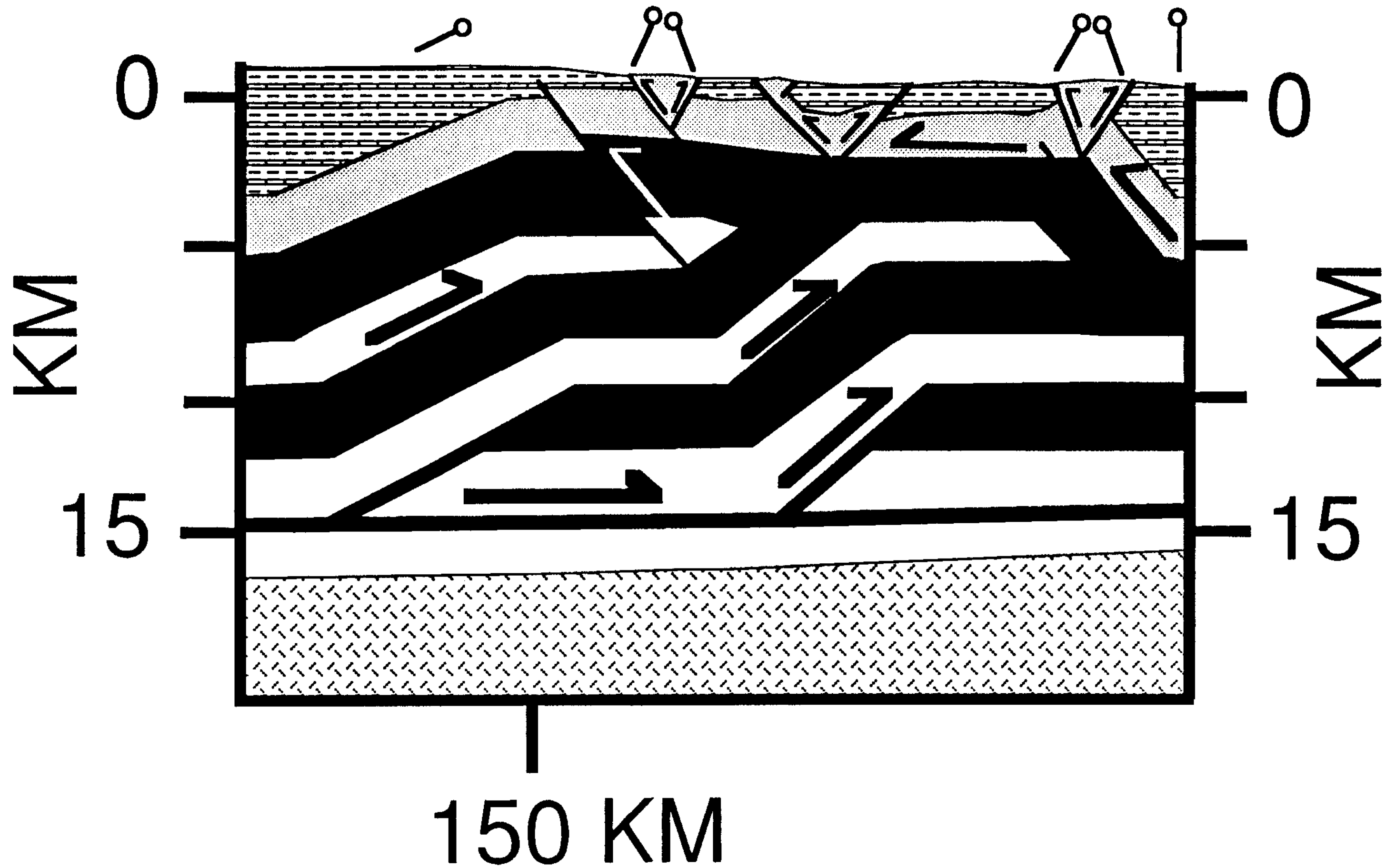


Figure 4.12

Figure 4.13. Balanced (A) and retrodeformed (B) structural cross-sections from the Indus foredeep across the Sulaiman mountain system in Pakistan. 349 km long deformed section (4.13A) restores to 727 km (4.13B) which gives maximum shortening of 378 km. Minimum shortening estimates of 308 km (see discussion) gives a shortening of 353 ± 25 km in the cover sediments of the Indian subcontinent. Missing roof-sequence is interpreted to be removed primarily by erosion along a major passive-backthrust. Letters identifying individual horses in the duplex sequence are from the individual mountains and from the geographic domains. From north to south these areas are Z1-Z3 = Zhob valley, L1-L3 = Loralai valley, D1-D3 = Duki Valley, M1 -M2 = Mari, T1-T2 = Tadri, K = Kurdan, D = Danda, P = Pirkoh, L = Loti (future horse). Numbers between the white dots and the black dots within the individual horses in the retrodeformed section show the length of the horse and the associated displacement in kilometers.

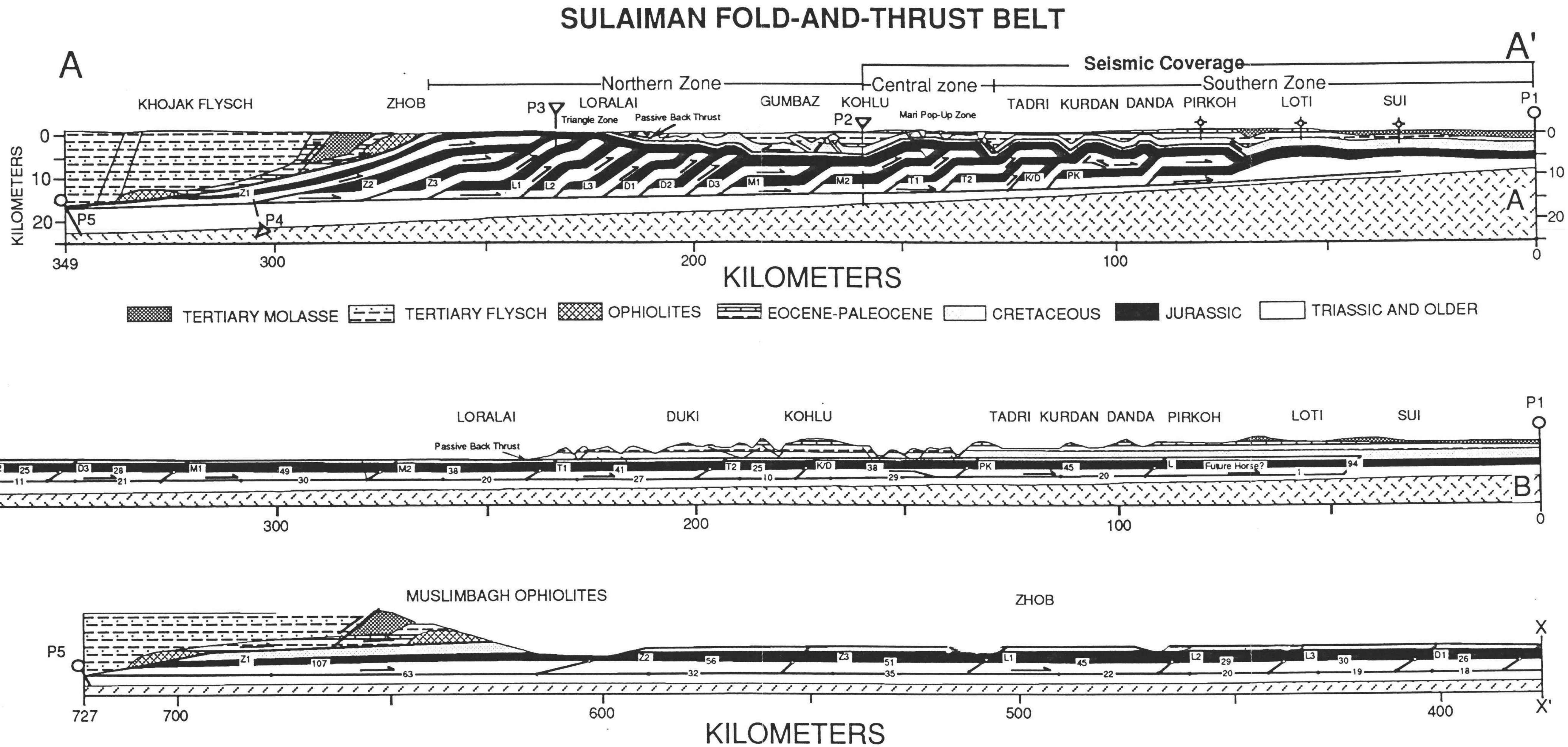

SULAIMAN FOLD-AND-THRUST BELT
A
A'
Seismic Coverage
Northern Zone
Central zone
Southern Zone
KHOJAK FLYSCH
ZHOB
P3
LORALAI
Triangle Zone
Passive Back Thrust
GUMBAZ
KOHLU
P2
Mari Pop-Up Zone
TADRI KURDAN DANDA
PIRKOH
LOTI
SUI
P1
KILOMETERS
P5
P4
349
300
200
100
0
KILOMETERS
TERTIARY MOLASSE
TERTIARY FLYSCH
OPHIOLITES
EOCENE-PALEOCENE
CRETACEOUS
JURASSIC
TRIASSIC AND OLDER
LORALAI
DUKI
KOHLU
TADRI KURDAN DANDA
PIRKOH
LOTI
SUI
P1
X
X'
Passive Back Thrust
Future Horse?
B
300
200
100
0
MUSLIMBAGH OPHIOLITES
ZHOB
P5
X
X'
727
700
600
500
400
KILOMETERS

Figure 4.13

passive-backthrust, and the Loralai triangle zone (Figs. 4.5 & 4.13). Hot springs discovered from the Loralai triangle zone (region between extensive faults of opposing vergence, terminology from Gordy et al, 1977) probably relate to the faults. The balanced section shows an intact passive-roof sequence about 150 km long (Fig. 4.13). Such a long continuous passive-roof sequence poses the problem of a means to accommodate shortening strain in the roof sequence. However, structures of similar magnitude are reported in the literature from the Appalachians (Roeder et al, 1978; Berg et al, 1980; Boyer and Elliot, 1982), Papuan, New Guinea (Hobson, 1986); and the Brooks Range, Alaska (Wallace, 1990). Relatively tight folds in the roof sequence (Hunting Survey Corporation, 1961; Bhatti et al, 1984) in this zone are interpreted as detachment folds in the passive-roof sequence.

In the northern Sulaiman fold belt the passive-roof sequence emerges in the Loralai valley (Figs. 4.5 & 4.13), where the structure is a triangle zone (terminology from Price,1981). Hot springs found in the Loralai triangle zone may relate to the faults. Such structures associated with mountain fronts are reported from the Canadian Rockies by Bally et al (1966), Jones (1982), and Vann et al (1986), and from the Himalayas by Lillie et al (1987) and Jaswal et al (1991).

In the Loralai triangle zone of the Sulaiman fold belt, massive, shallow water Jurassic (Chiltan) limestone (Iqbal and Shah, 1980) crops out at the surface in nearly symmetrical anticlines (Fig. 4.5). North of the Loralai triangle zone, massive Chiltan limestone is replaced by more distal, slope and rise facies (medium bedded limestone and intercalated shales) of Jurassic and Triassic age. The structure changes from a duplex geometry to simple ramp-and-flat geometry, and is dominated by detachment folding (box and kink folds; see maps of Hunting Survey Corporation, 1961). It is presumed that a fault with considerable shortening must be present in the Loralai valley (Loralai thrust in Fig. 4.5), to emplace the more distal Jurassic facies and older rocks against the shallow water Jurassic limestone. A similar interpretation is suggested for this facies change by Kazmi (1981). This part of the balanced section is primarily area balanced. Complex folds (Hunting Survey Corporation, 1961) above the major flat (Z1) south of the Zhob ophiolite is not shown because they are too small for the scale of the cross-section (Fig. 4.13). The Zhob thrust sheet (Z1) is overlain by Muslimbagh ophiolites in the Zhob valley. Paleocene to early Eocene emplacement of the ophiolites (Allemann, 1979; Otsuki et al, 1989) over shelf sediments records the first event of collision along the precollisional passive margin. Subsequently much of the Khojak flysch was deposited and deformed during Eocene to Miocene, probably as a submarine fan on the oceanic crust of the closing Neo-Tethyes ocean (Lawrence and Khan, 1991a).

Palinspastic Restoration

Balanced and retrodeformed cross-section (Fig. 4.13) have 2 pinlines, P1 and P5, starting in the Sulaiman foredeep and ending at an arbitrary cutoff point at the Muslimbagh allochthon, and three intermediate reference lines, P2, P3, and P3. The northernmost point is at the edge of early emplaced ophiolites and melange, the shortening of which is not dealt with in this study. These pin and reference lines are selected to reflect variations of the seismic coverage, stratigraphy, and other uncertainties along the balanced cross-section (Fig. 4.13A). P1, through the undeformed rocks, is in the Sulaiman foredeep. P2 is through the M1 and M2 duplex sheets at 159 km at the limit of the seismic coverage. Thus P1 to P2 is the area with good subsurface control and most confident reconstruction. P3 is through the footwall of the Z3 duplex sheet at the northernmost limit of exposure of massive (platform) Jurassic limestone in the Loralai valley. P4 is through the footwall cutoff of Z2. Buried rocks between P3 and P4 may include the Jurassic transitional slope facies that are onlapped by the Loralai thrust (Fig. 4.5). There is no thickness control on units in this area and constant thicknesses unlikely shelf sediments are extrapolated in the reconstruction. North of P4 shortening and structures are poorly constrained and the P4 to P5 portion is included mainly to show the possible complete section across the reconstructed Mesozoic margin. Due to the multiple uncertainties in the northern section, no effort has been made in the retrodeformed section to include a realistic continental margin geometry. The northern part of figure 4.13 is intended only for shortening estimates. After gravity data are discussed below, more geometrically realistic models are attempted.

It is important to point out that the base of the Jurassic limestone is picked to calculate the total shortening. This horizon is part of the duplex structure that has never been emergent or eroded except in the northern part of the Loralai triangle zone (Fig. 4.13A). Thus, the problem of eroded section length uncertainties is negligible, as little or no erosion has occurred. Thus the retrodeformed cross-section (Fig. 4.13B) of this study provides a maximum estimate of shortening. This is in contrast to most shortening estimates from balanced sections which are minimal estimates due to missing sections along emergent faults (Coward and Butler, 1985).

The deformed section between the pin lines P1 to P5 (Fig. 4.13A) is 349 km long. The frontal half part of the section between km marks 0 to 159, P1 to P2, is constrained by seismic reflection data (Figs. 4.6 & 10) and is balanced by the line-length method. This part restores to an undeformed length of 280 km for a shortening of 121 km. The second part of the cross-section, between kilometer marks 159 to 349, P2 to P5, is 190 km long and restores to an undeformed length of 447 km, that gives maximum shortening of 257 km. This part is primarily area balanced maintaining the stratigraphic thickness documented below Kohlu syncline by seismic data and using the documented thickness in the field for the section north of the Loralai. All together the 349 km long deformed section across the Sulaiman fold belt (Fig. 4.13A) restores to a maximum undeformed length of 727 km (Fig. 4.13B), which gives a maximum shortening of 378 km. Section may thicken between Kohlu and Loralai, but no data is available to provide control. I measured the area labelled "problem" on figure 4.11 and considering the location of ocean/continent boundary discussed in proceeding sections assumed, that the section thickens 25% by its north end. This results 207 km of shortening of the northern portion, or total minimum shortening of 328 km, for an overall shortening of 353 ± 25 km (50%). Only a fraction of shortening (<1 km) is accommodated by the broad frontal folds (Sui and Loti), over a distance of about 55 km. Shortening within the passive-roof sequence is 20 km. This is accommodated by surface faults and folds. All additional shortening in the roof sequence is taken by an emergent passive-backthrust in the Loralai triangle zone in this interpretation.

The 50% shortening in the central portion of the Sulaiman fold belt is similar to 50% in the Kohat Plateau south of the main Boundary thrust (McDougall and Hussain, 1991). However, it is smaller than the about 60% shortening estimated along cross-section C-C' in Fig. 4.2 for western Sulaiman (Banks and Warburton, 1986). Smaller amount of shortening (50%) along cross-section A-A' compared to C-C' (60%) (Fig. 4.2) could be explained in two ways. (1) The central Sulaiman is translated farther south onto the foreland; that is, the length of the deformed section between the pin lines is about 3.5 times greater in the central Sulaiman Range (349 km: 100 km). (2) The Sulaiman lobe along the edge of the Indian subcontinent (Fig. 4.2) may experience variable shortening due to transpression.

In the northern Pakistan estimates of shortening in cover sediments of the Indian subcontinent related to the Himalayan orogeny are 475 km-500 km (Coward and Butler, 1985; Izatt, 1990). This is greater than the 353 ± 25 km estimates of shortening from the Sulaiman Range. However, this number may be greater in northern Pakistan due to more section under Kohistan (Lillie, 1991) and/or unknown, but significant, lengths of missing section eroded away along emergent faults.

GRAVITY MODELLING

Gravity Data and Constraints

Gravity modelling was done for an 800 km long profile extending from the Sulaiman foredeep to eastern Afghanistan (B-B' in Figs. 4.2 & 4.14). Regional Bouguer gravity data along this profile from kilometer marks 0 to 250 are from an OGDC partially published map at a contour interval of 2 mgals (published part for the southern Indus basin by Quadri and Shuaib, 1986). The values from kilometer marks 250 to 800 (Fig. 4.14) are from the Marussi (1976) map which has a 50 mgal contour interval. Observed Bouguer gravity values obtained from Marussi (1976) were compared with values given by McGinnis (1971) in Afghanistan and with recently collected data by the Geological Survey of Pakistan (GSP) at an interval of 5 km between kilometer marks 250 to 350 in the Loralai, Muslimbagh, and Duki areas of the central Sulaiman fold belt (Khurshid, 1991). The regional gravity values from Marussi (1976) are too coarse to reveal any anomalies related to shallow structures. As a result most of the gravity profile is smooth with anomalies near zero in the southern Sulaiman foredeep, then continually decreasing northward to about -190 mgals along the Chaman fault and -265 mgals farther north in Afghanistan (Fig. 4.14).

Estimates of the depth to the top of crystalline basement, see above, and the structural interpretation of the balanced cross-section (Fig. 4.13) provided the basic layers for gravity modelling, south of the Muslimbagh ophiolite. This data set is combined with the geological maps (Hunting Survey Corporation, 1961; Kazmi and Rana, 1982) in Pakistan and published work and maps (Andritzky et al, 1971; Wittekindt and Weippert, 1973; Bordet, 1978; Boulin, 1981; Tapponnier et al, 1981) in Afghanistan to construct a simplified geologic cross-section to model the observed Bouguer gravity profile from the Sulaiman foredeep to the Chaman fault in eastern Afghanistan (Fig. 4.14). The cross-section is simplified by showing the basement at the surface north of the Chaman fault because of shallow exposures of crystalline rocks north of the Chaman fault (Andritzky et al, 1971; Wittekindt and Weippert, 1973).

The densities for the sediments are obtained by converting seismic reflection velocities from the eastern (Humayon et al, 1991) and southern (Jadoon et al, 1991) Sulaiman Range. Table 1 shows estimates of average P—wave velocities and appropriate densities used for the sedimentary package above the crystalline basement. In the Khojak flysch zone and undifferentiated crystalline rocks shown in the Afghan block (Fig. 15A) densities are approximated based on the known densities for the roof and duplex

Figure 4.14. Bouguer gravity anomaly profile and two dimensional geologic sketch along line B-B' in Fig. 4.2. Observed Bouguer gravity data between mark 0-250 km are from an unpublished Bouguer gravity map by the Oil and Gas Development Corporation of Pakistan (OGDC). Gravity data from mark 250 to 800 km are from the map of Marussi (1976). These data are consistent with observations reported by McGinnis (1971) for Afghanistan, and Khurshid (1991) for the zone between the 350-450 km marks. Depth to the basement and structural interpretation in the cover sediments are based on the seismic reflection interpretation from the Sulaiman Ranges (line A-A' in Figs. 4.2 & 4.13; Jadoon and others, 1991). CF = Chaman Fault, KFL = Katawaz Flysch Basin (Neogene), MBO = Muslimbagh Ophiolite, PRS = Passive-roof sequence, SFB = Sulaiman Fold Belt, and UD = Undifferentiated.

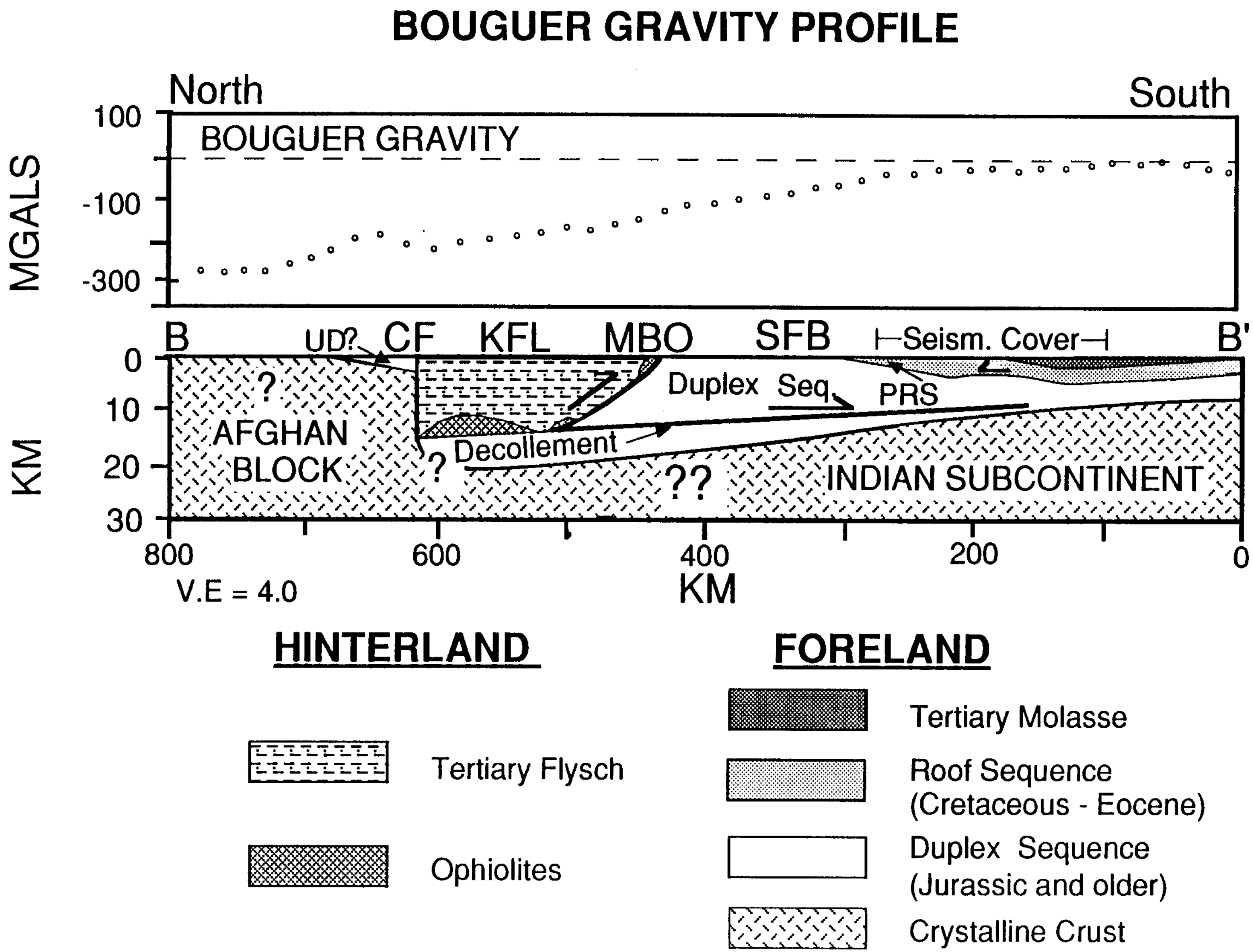

BOUGUER GRAVITY PROFILE
North
South
MGALS
100
-100
-300
BOUGUER GRAVITY
B
UD?
CF
KFL
MBO
SFB
Seism. Cover
B'
0
10
20
30
KM
?
AFGHAN
BLOCK
Duplex
Seq
PRS
Decollement
?
??
INDIAN SUBCONTINENT
800
600
400
200
0
V.E = 4.0
KM
HINTERLAND
FORELAND
Tertiary Molasse
Tertiary Flysch
Roof Sequence
(Cretaceous - Eocene)
Ophiolites
Duplex Sequence
(Jurassic and older)
Crystalline Crust

Figure 4.14

Figure 4.15. Two dimensional density and tectonic model for observed Bouguer gravity anomaly across the Sulaiman fold belt and the Chaman fault zone. Density contrasts are in gm/cm^3 relative to the crystalline crust. See figure 4.14 for details about the source of observed Bouguer gravity data. Depths to the basement, structural interpretation in the cover strata, and approximate densities are controlled by well logs, and seismic reflection profiles from the southern (Jadoon et al, 1991; Figs. 4.6 & 4.9, Table 1) and eastern Sulaiman Ranges (Humayon et al, 1991). Abbreviations are the same as in figure 4.14. Figs. 4.15A & B show the contribution to Bouguer gravity anomaly from the sedimentary strata and mantle, respectively. Fig. 4.15C shows the close fit between observed and calculated Bouguer gravity profiles when the two contributions are added. Fig. 4.15D represents a two dimensional tectonic model across the Indian/Afghan collision zone based on the density model in 4.15C.

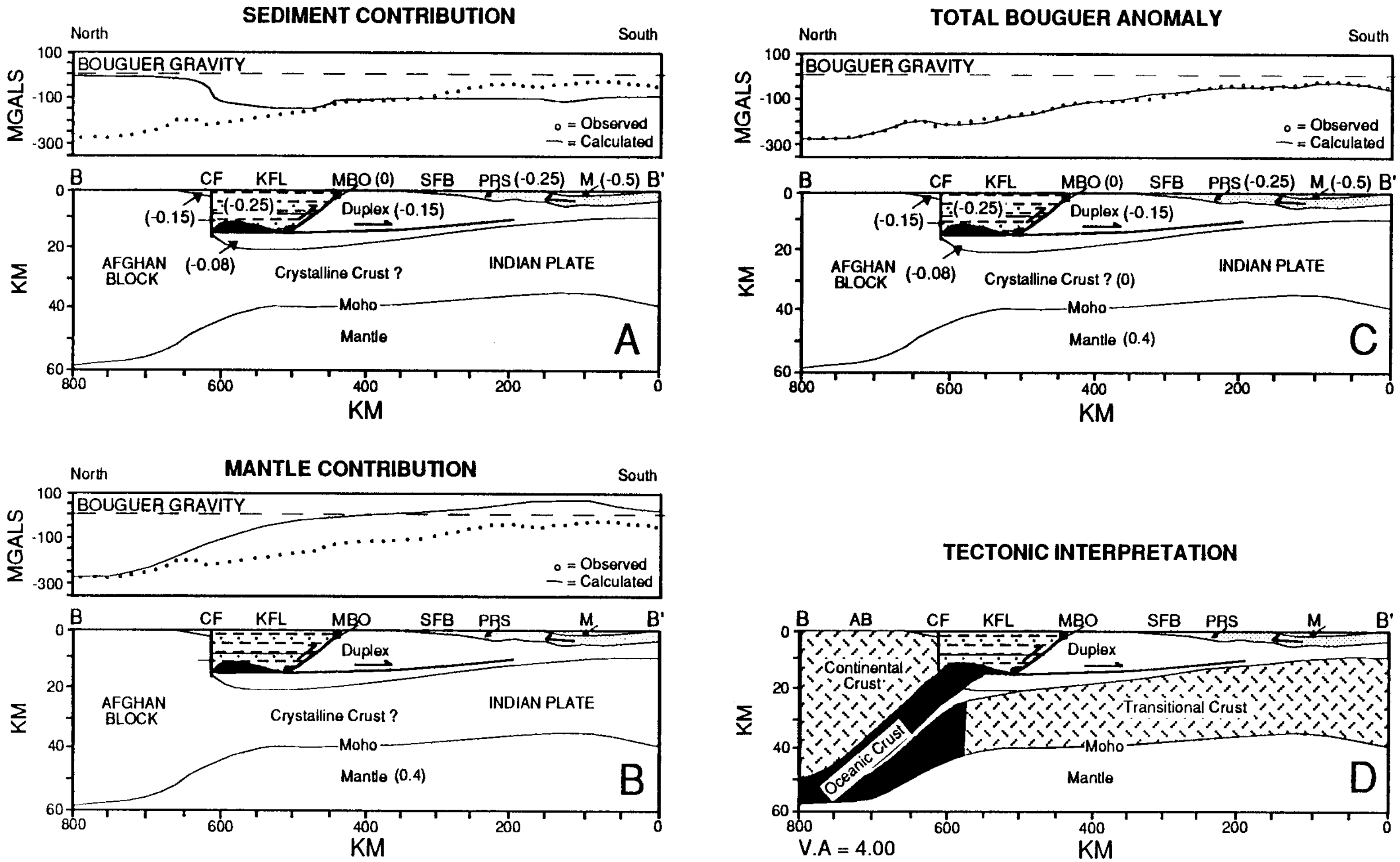

SEDIMENT CONTRIBUTION
TOTAL BOUGUER ANOMALY
MANTLE CONTRIBUTION
TECTONIC INTERPRETATION
North
South
BOUGUER GRAVITY
MGALS
o = Observed
— = Calculated
B
B'
CF
KFL
MBO (0)
SFB
PRS (-0.25)
M (-0.5)
AB
(-0.15)
(-0.25)
(-0.08)
Duplex (-0.15)
Duplex
AFGHAN BLOCK
Crystalline Crust ?
Crystalline Crust ? (0)
INDIAN PLATE
Moho
Mantle
Mantle (0.4)
Continental Crust
Oceanic Crust
Transitional Crust
KM
V.A = 4.00
A
B
C
D

Figure 4.15

TABLE 4.1. ESTIMATED AVERAGE DENSITIES OF GEOLOGIC AND STRUCTURAL UNITS

Geologic and Structural Units	Approximate Velocity (km/sec)	Approximate Density (gm/cm^3)
Molasse (Tertiary)	2.5-3.0	2.3
Flysch (Tertiary)	No Seismic Available	2.55-2.65
Roof Sequence (Eocene-Cretaceous)	2.8-4.5	2.55
Duplex Sequence (Jurassic and older)	4.5-5.2	2.65

Note: The P-wave velocities are from seismic reflection interpretations from the southern (Jadoon et al. 1991) and eastern (Humayon et al. 1991) Sulaiman Range. The approximate densities are estimated from Nafe and Drake curve in Sherif (1984).

sequences in Table 1. The density for the crystalline crust was assumed to be 2.8 gm/cm^3. This is based on about 6 to 7 km/sec of P-wave velocities from earthquakes (Menke and Jacob, 1976; Kaila, 1981) and seismic refraction data (Trehu et al, 1989). The P-wave velocities vary between 7-8.6 for the upper mantle (Sheriff, 1984; Menke and Jacob, 1976; Kaila 1981; Trehu et al, 1989). On the basis of these observations an approximate density of 3.2 gm/cm^3 is considered for the upper mantle to model the gravity profile. The density model in figure 4.15 shows relative density contrasts with an assumed density of 2.8 gm/cm^3 for the crystalline crust.

Bouguer Gravity Modelling and Results

Bouguer gravity anomalies consistently decrease northward from near zero over the Mari-Khandkot high in the Sulaiman foredeep, to about -190 milligals along the Chaman fault and -265 milligals in central Afghanistan (Fig. 4.14). As a first approximation, low values of Bouguer gravity anomalies in the Sulaiman fold belt can be compared with (1) those of the Salt Range/Potwar plateau and the Main Himalaya in northern Pakistan (Duroy and et al, 1989) and (2) bouguer gravity modelling along two generally east-west cross-sections across Sulaiman/Kirthar Ranges (Khurshid, 1991; Rahman, 1969). In the northern Potwar Plateau about -160 mgals of Bouguer gravity values are modelled to suggest a full thickness crystalline crust (Duroy et al, 1989). The thickness of the sediments in the seismic reflection lines is about 9 km there (Lillie, 1987; Jaswal, 1991). Similar gravity modelling of higher Bouguer gravity anomalies from the Sulaiman Range requires an even thicker continental crust (Rahman, 1969). Alternatively, these large anomalies may be compensated by a shallower mantle underneath the Sulaiman Range (Khurshid, 1991). This second preferred hypothesis, suggesting a transitional crust underneath the Sulaiman Range, is consistent with the presence of a thick (about 7 km) platform sequence beginning at the southern Sulaiman front (Jadoon et al, 1989). This supports the interpretation of an earlier stage of underthrusting in the Sulaiman fold belt compared to northern Pakistan. If the Sulaiman fold belt is going through a very early stage of continental convergence, then the Bouguer gravity values should become less negative across the Chaman fault in eastern Afghanistan. (The response of Bouguer gravity anomaly values to successive stages of convergence is discussed in Lillie, 1991) Instead, the northward gradient of Bouguer gravity anomaly values continues to decrease in Afghanistan which suggests thickening of crystalline crust across the plate boundary.

The Bouguer gravity profile has a general gradient of -0.35 mgal/km towards the north. This can in general be interpreted as a combined result of the sediment thickness and Moho depth variations (Fig. 4.14). Figures 4.15A and 4.15B separate the effect of these contributions on the observed Bouguer gravity profile. Figure 4.15A (sediment contribution) shows the superimposed gravity lows and highs due to low density molasse sediments in the Sulaiman foredeep, high density Muslimbagh ophiolites, and the crystalline crust of the Afghan block against the Khojak flysch north of the Chaman fault. Figure 4.15B (mantle contribution) shows the negative northwards gradient due to the northwards dipping Moho with a gentle inclination of about 1°. This overall gradient is modified by a slight upwards convexity of the Moho in the Sulaiman foredeep region and a steeper Moho gradient at the margin of the Afghan block. These effects are interpreted as a result of tectonic compression in the Sulaiman foredeep and thickening of the crust of the Afghan block. The slight upward convexity to mantle contribution due to high density mantle material is consistent with the distribution of Airy isostatic anomalies from the Sulaiman Range (Khurshid, 1991). Near zero Airy isostatic anomalies (McGinnis, 1971; Marussi, 1976) from eastern Afghanistan could mean that the region north of the Chaman fault is near a state of Airy isostatic equilibrium. The region just south of the Chaman fault in the Khojak flysch belt is overcompensated (mass deficiency). In contrast, the frontal Sulaiman and adjacent foredeep region is undercompensated (mass excess). Khurshid (1991) suggests that the mass excess in the foreland is shallow mantle material from the Mesozoic rifted continental margin of India, while the deficiency beneath the interior is due to Cenozoic collision.

Figure 4.15C shows the best match between observed and calculated anomalies. This is obtained by combining the effect due to sediment and mantle contributions (Figs. 4.15A & 4.15B). The gravity model depicts the depth to the Moho as about 35 km at the deformation front of the Sulaiman fold belt. The Moho is flexed upward in the foredeep. North of the foredeep it has a gentle northward dip of about 1.1° (20m/km) until it approaches the Chaman fault zone. The depth to the Moho below the Chaman fault zone is about 42 km along the transect. It deepens abruptly across the Chaman fault zone from about 42 km south of the Chaman fault to about 57 km north of the fault. A steep northward dip of 7.8° (136m/km) to the Moho below the Chaman fault zone results from this model. The Moho regains its gentler northwards dip north of the Chaman fault system. About 57 km depth in eastern Afghanistan is consistent with previously interpreted crustal thicknesses of 53 km in central Afghanistan (McGinnis, 1971) and about 55 km close to the Chaman fault (Rahman, 1969). Figure 4.15D suggests my preferred tectonic interpretation of the density model in Fig. 4.15C. Tectonic interpretation is discussed in a proceeding section.

DISCUSSION

Structural Style and Geometry

In this study the Sulaiman fold belt is interpreted to have a passive-roof duplex style of deformation. This is consistent with interpretations from the western (Banks and Warburton (1986) and eastern (Humayon et al, 1991) Sulaiman Ranges. However, it is contrary to simple ramp-and-flat geometry for the evolution of the Sulaiman fold belt proposed by Bannert et al (1989). Balanced and retrodeformed cross-sections show that the duplex sequence is formed by massive Jurassic limestones and older rocks and is detached from the crystalline basement along a sole thrust (decollement). The duplex sequence is separated from the roof sequence by a passive-backthrust in thick Cretaceous shales. Structures at the surface in the passive-roof sequence may or may not reflect the shape of the deep structures.

Passive-roof sequence

Boyer and Elliot (1982) reported a kinematic model for the development of duplexes with floor and roof thrusts with motion only towards the foreland (Fig. 4.16A). This duplex geometry provides one logical solution to explain the structurally duplicated orogenic wedges whose surface expression lacks faults with significant shortening on the ground. Examples of this geometry in which the apparently unbroken surface sheet extends large distances toward the hinterland are known, and the Sulaiman lobe is one of the clearest examples. However, a mechanical problem with such geometries is how an equal amount of shortening strain can be accommodated in both the roof and duplex sequences. Various models involving backthrusting of the roof sequence and/or passive behavior of the roof sequence attempt to resolve this problem.

How far a passive-roof sequence may extend has not yet been resolved. Suppe (1980) shows a 14 km long passive-roof sequence in Taiwan. Jones (1982) postulates a 50 km length for a backthrust sequence in the Alberta foothills. Continuous roof sequences extending over several duplex horses are reported from the Brooks Range of Alaska (Vann et al, 1986; Wallace, 1990), from the Appalachians (Geiser, 1988a, 1988b), and the Papua, New Guinea, thrust belt (Hobson, 1986). This study suggests a continuous passive-roof sequence of about 150 km in the Sulaiman fold belt of Pakistan (Fig. 4.13A).

To a minor extent, shortening in the roof-sequence across-strike may be accommodated by uplift and folding. But how does one accommodate major shortening strain in the roof sequence? Existing models of known examples are explored below to find an explanation that best fits the situation in the Sulaiman fold belt.

1) Foreland-verging emergent roof-sequence. A foreland emergent roof–sequence is a continuous structure that emerges along a large displacement, foreland-verging fault at one of two locations:

A) Emergent allochthonous roof-sequence (Geiser, 1988b). The roof duplex may become emergent in the foreland (Fig. 4.16B; Boyer and Elliot, 1982; Vann et al, 1986; Geiser, 1988b); examples are the Jura and Swiss Plain, and the Mackenzie Mountains area of Canada. As proposed, this model involves no backthrust motion, however, if the roof sequence moves forward more slowly than the duplexes, a passive-backthrust component of motion can be introduced.

B) Superficial decollement in the roof-sequence. The roof duplex may develop an extensive decollement within the roof sequence (Fig. 4.16C) similar to that in the main Brooks Range thrust plate south of the Romanzof Mountains in Alaska (Vann et al, 1986). In active fold and thrust belts, this may be recognized by an anomalously thick roof sequence. This model restricts backthrust motion to the leading portion of the foreland system.

2) Layer-parallel shortening. Geiser (1988a, 1988b) argues that layer parallel shortening within the roof sequence is a major mechanism to accommodate missing shortening in cross-sections from the Appalachian Valley and Ridge Province (Fig. 4.16D). This must involve substantial pressure solution, cleavage development, and section thickening in the roof sequence. Presumably it requires that the roof sequence be very thick or buried at the time of deformation in order that low grade metamorphic processes may operate.

3) Detachment folds. This mechanism is proposed by Wallace (1990) and was illustrated without discussion by Dahlstrom (1970), with examples from the northeastern Brooks Range, Alaska, and the Canadian Rockies. It accommodates shortening above the roof thrust mainly by detachment folds (Fig. 4.16E). By this mechanism the relative shortening between the roof and duplex sequences is reduced by the amount of shortening in the folds.

4) Passive-backthrust. Banks and Warburton (1986) recognized several overstep-backthrusts emerging from a passive-roof thrust (upper detachment), all with a backthrust sense of vergence. In each case the backthrust emerges from the tip of a duplex. The emplacement of the duplex uplifts and rotates the roof sequence passively

without any significant forward translation. Uplift and rotation in rocks over the foreland propagating duplex horse creates steep monoclinal dips to the roof sequence rocks at the foredeep margin. As a result, the roof sequence becomes emergent along a backthrust and is removed primarily by erosion (Fig. 4.16F). Very long preserved roof sequences are precluded by this geometry.

5) Deformation prior to deposition. This mechanism first suggested by Geiser (1988b) requires deformation prior to or simultaneous with the deposition of the roof sequence (4.16G). In this case much of the duplex shortening in the hinterland is accomplished before the roof-sequence is deposited. Deposition farther toward the foreland, however, is continuous. Thus the relative displacement between the roof-sequence and the duplexes is largest just south of the end of the unconformity.

6) Major passive-backthrust. None of the above mentioned processes appear to operate as a main shortening mechanism for the long passive-roof sequence of the central Sulaiman Range (Fig. 4.13). Instead this 150 km long, intact passive-roof sequence is emergent along a major passive-backthrust in the Loralai valley. This is the longest passive-roof sequence I have found in the literature (Hobson, 1986, shows about 120 km). No significant break in this fault has been recognized from its southern tip line to the Loralai valley which implies that backthrust motion on this fault must be equivalent to the forethrust motion in the originally underlying duplex sequence. The minimum relative displacement on the passive-backthrust under the roof sequence is 106 km (Fig. 4.17). Thus, in the early stages of structural development, a hinterlandward emergent continuous passive-roof sequence may extend over several duplex horses (Fig. 4.13A). North of Loralai, the roof sequence has largely been removed by erosion and is no longer a continuous sheet. How this motion is accomplished mechanically remains a significant problem.

The descriptive situation is a very long passive-roof sequence that has an emergent backthrust at its northern termination along which material has been removed by erosion (Fig. 4.16H). If the roof sequence continued uninterrupted to the north end of the thrust system, more than 300 km of length would have to be removed by erosion (Fig. 4.13). This is similar to figure 4.16D in that both have an intact roof sequence over a greater distance, but it is different from figure 4.16D in that the emergent fault is a passive-backthrust in the hinterland of the Sulaiman fold belt instead of a foreland verging fault in the foredeep basin. Mechanically, it could pose serious problems if rugged topography is present as this would make continued relative displacement of the roof sequence difficult. However, the Sulaiman fold belt may be an exception due to gentle (<1°) topography and the presence of very thick shale (Sembar formation) at the decollement horizon. More than

Figure 4.16. Conceptual models to propose shortening in the roof sequences based on practical examples around the world.

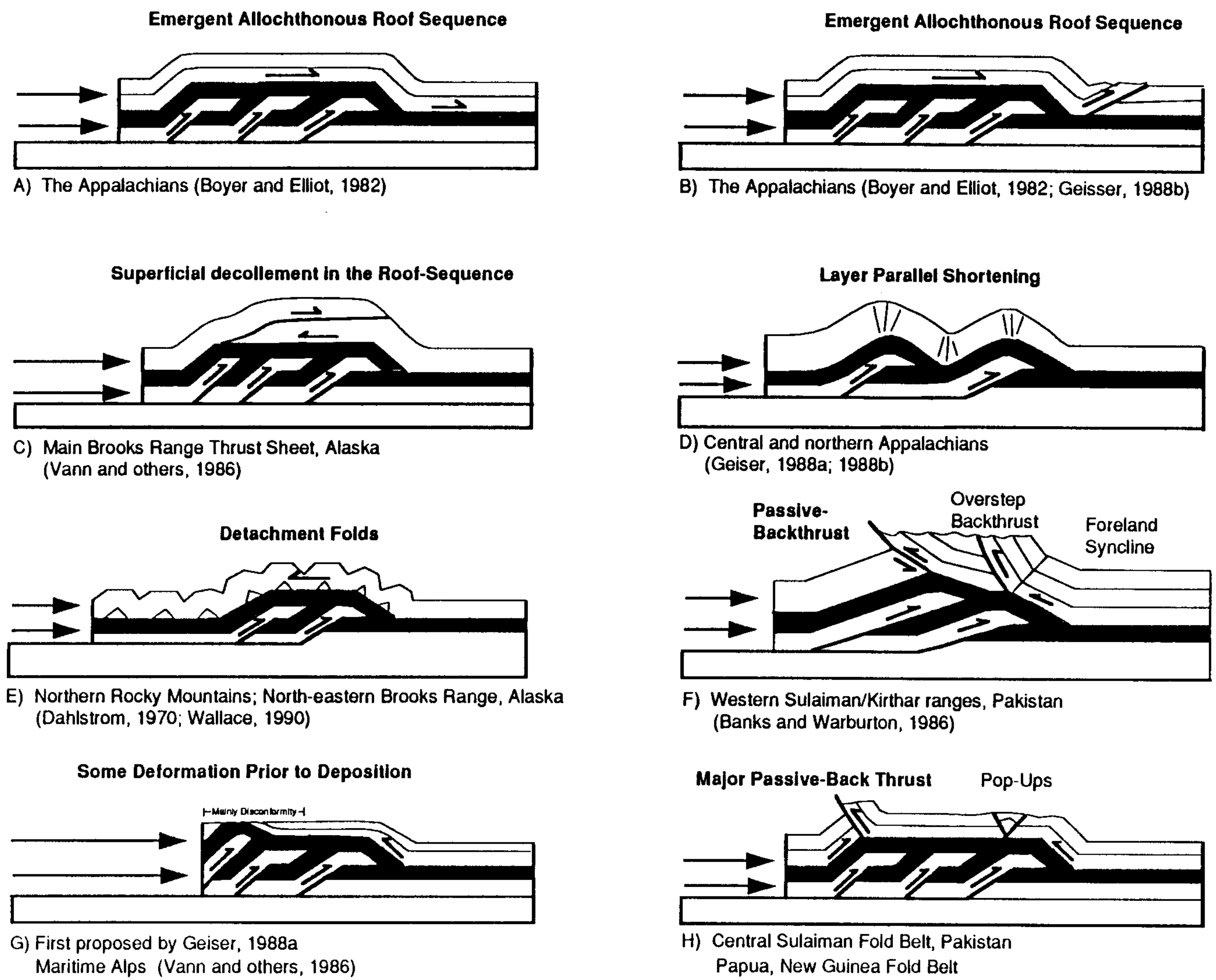

Emergent Allochthonous Roof Sequence
A) The Appalachians (Boyer and Elliot, 1982)
Emergent Allochthonous Roof Sequence
B) The Appalachians (Boyer and Elliot, 1982; Geisser, 1988b)
Superficial decollement in the Roof-Sequence
C) Main Brooks Range Thrust Sheet, Alaska
(Vann and others, 1986)
Layer Parallel Shortening
D) Central and northern Appalachians
(Geiser, 1988a; 1988b)
Detachment Folds
E) Northern Rocky Mountains; North-eastern Brooks Range, Alaska
(Dahlstrom, 1970; Wallace, 1990)
Passive-
Backthrust
Overstep
Backthrust
Foreland
Syncline
F) Western Sulaiman/Kirthar ranges, Pakistan
(Banks and Warburton, 1986)
Some Deformation Prior to Deposition
Mainly Disconformity
G) First proposed by Geiser, 1988a
Maritime Alps (Vann and others, 1986)
Major Passive-Back Thrust
Pop-Ups
H) Central Sulaiman Fold Belt, Pakistan
Papua, New Guinea Fold Belt

Figure 4.16

Figure 4.17. The plot of the cumulative length of the duplex horses against the cumulative displacement from the tip of the duplex structure to determine relative displacement between two chosen points. Figure suggests 106 km of minimum relative displacement between roof and duplex sequence along a 170 km long passive-backthrust in the Sulaiman fold belt of Pakistan. Letters identifying individual duplex horses are the same as in Fig. 4.13. Lx and Dx refers to the length and displacement of individual duplex horse.

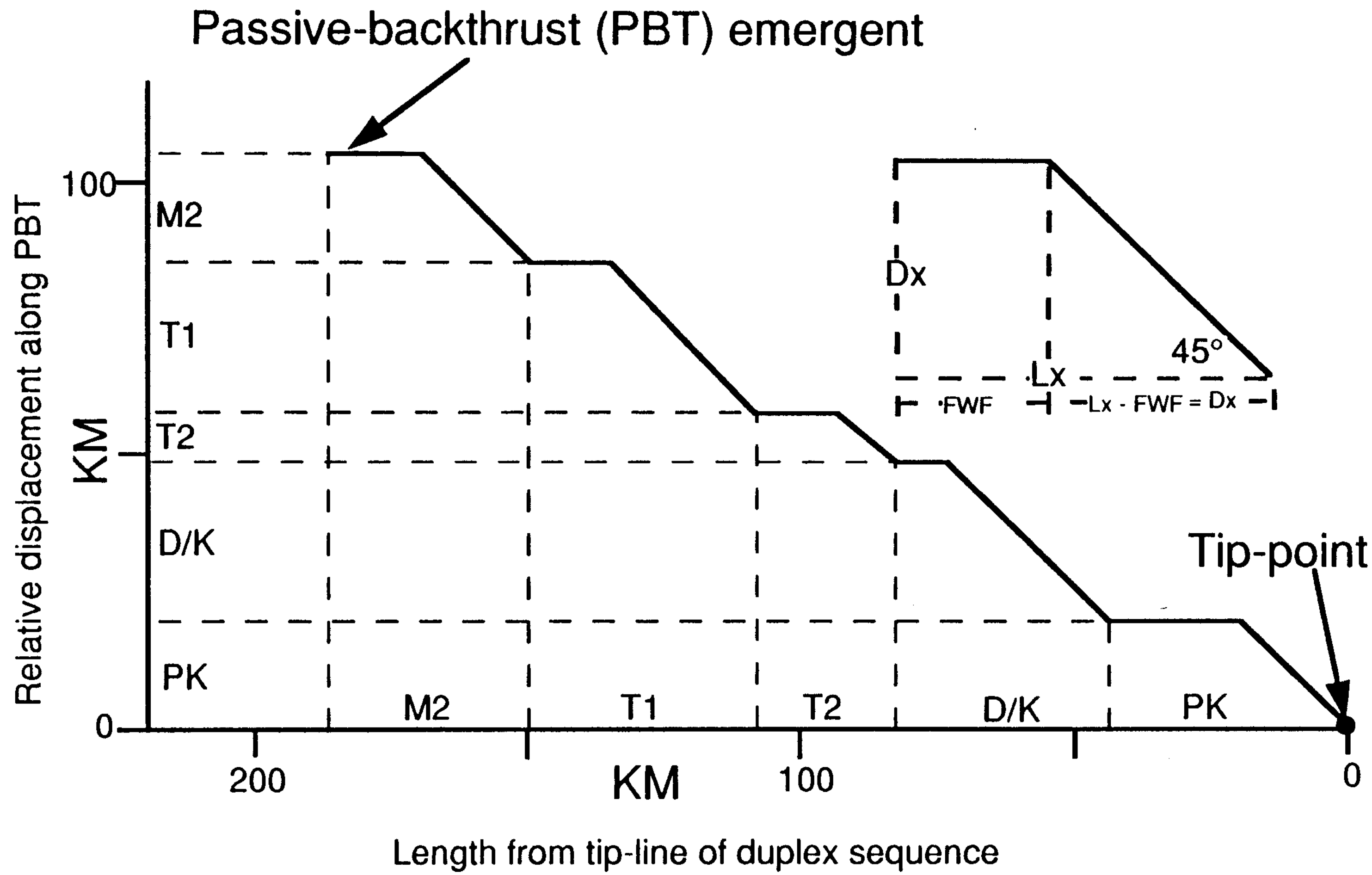

Passive-backthrust (PBT) emergent
100
M2
T1
T2
D/K
PK
0
Relative displacement along PBT
KM
Dx
Lx
45°
FWF
Lx - FWF = Dx
Tip-point
M2
T1
T2
D/K
PK
200
KM
100
0
Length from tip-line of duplex sequence

Figure 4.17

1700 m of Sembar shale have been drilled in the Giandari well from the Sulaiman foreland (Fig. 4.9). This shale is extensively distributed along the emergent Loralai backthrust in the broad (>15 km wide) Loralai valley (Fig. 4.5).

In the missing portions of the roof-sequence north of Loralai valley, several of the other models of passive roof deformation could have been operative such as internal folding or shortening of the roof-sequence (Figs. 4.16 D & E), other major backthrusts (Figs. 4.16 F & H), and deformation before deposition of the roof-sequence (Fig. 4.16G). The last may be important as significant deformation occurred during ophiolite emplacement (latest Cretaceous to Eocene) and a major unconformity developed at that time. Further study of this possibility is needed.

The roof sequence does show secondary hinterland and foreland verging faults and associated pop-ups. Displacement along secondary faults never exceeds more than 2-3 km. Due to minor throw, the roof sequence nowhere becomes emergent along these faults (Figs. 4.10 & 4.12). Much of the second band of seismicity (Quittmeyer et al, 1979) and probable neotectonic features are located along these probably active faults (see above). These faults may represent an early stage of development of a new major overstep backthrust (Fig. 4.16F & H). However, these faults do not show ground rupture (T. Nakata, in preparation). In contrast northern zone that is presently aseismic does show active faults with ground rupture. Lack of seismicity in northern zone may be attributed with recurrent interval of earthquakes that could be large in the northern zone (T. Nakata, personnel communication). I think that the active faults in the northern zone may be related with out-of-sequence thrusting and activity along emergent passive-backthrusts. Presently the locus of activity may have shifted to the central zone where out-of-sequence faulting and an incipient overstep backthrust are in early stages of evolution.

Duplex structures

Below the roof sequence, the deep, major structures of the thrust system are duplexes. The retrodeformed cross-section (Fig. 4.13B) shows that the individual duplex horses are of variable length and relative displacement. This results in folds of variable symmetry, geometry, and tightness. The main structures are described below using terminology from Dahlstrom (1970), Boyer and Elliot (1982), Butler (1982), Suppe (1983); Banks and Warburton (1986), Boyer (1986), Mitra (1986), and Groshong and Usdansky (1988).

In the southern zone, Sui and Loti are broad, concentric frontal folds (Dahlstrom, 1970) formed at the tip of the decollement, primarily by buckle folds over the ductile rocks along the detachment horizon. Liu and Dixon, (1990) experimentally produced such folds in front of the duplexes. These folds are forelandward of ramp and duplex structures which start with the Pirkoh anticline (Fig. 4.13A). The Pirkoh anticline forms a significant topographic front. Much of seismic activity from the southern band (Quittmeyer et al, 1979) is probably located along blind faults below this topographic front.

From Pirkoh to Tadri (Figs. 4.3 & 4.13), the geometry of the surface folds reflects the shape of the duplex related fault-bend folds at depth. From south to north, Pirkoh, Danda, and Kurdan are interpreted as a fault-bend fold, overlap ramp anticline, and an intraplate fold, respectively. Unlike Pirkoh and Danda, which have foreland vergence, the intraplate Kurdan fold formed as a result of displacement along a passive-backthrust within the Kurdan duplex sheet (Jadoon et al, 1991 in press).

Deep structures below the Tadri anticline and the central zone are anticlinal stacks (overlapping ramp anticlines). In each case a structural hole of about 8 km below the roof sequence is filled by two duplex horses. Note the monoclinal dip of the roof sequence in front of M2 duplex horse (Fig. 4.13A). The Foreland vergent monoclinal dip of the M2 duplex horse could lock the hinterland vergent passive propagation of the roof sequence. The secondary structures at the surface between the Tadri anticline to Kohlu syncline may then develop due to increasing strain in this region. This zone of complicated surface structures called as the Mari pop-up zone (Jadoon and Khan, 1990b) is similar to structures shown in the roof-sequence in West Virginia (Parry,1978; Mitra, 1987).

The northern zone has a planar-roofed duplex below the Gumbaz structural depression and hinterland verging duplexes farther north. The excess space below the Gumbaz structural depression does not require two duplex horses to form an anticlinal stack (Fig. 4.11). Instead it can be filled by a single duplex horse (Fig. 4.13). This suggests that the Gumbaz structural depression in the roof sequence was produced by a change in structural style from anticlinal stacks in the central zone to fault-bend folding in the northern zone. The length of the M1 duplex horse and displacement along this horse below the Gumbaz structural depression is much larger than that on the preceding duplex horses (Fig. 4.13). This may be due to presence of relatively weak decoupling (along salt?) that resulted in greater translation and hence produced a change in structural style as that weak surface was overrun. Alternatively, relatively strong decoupling in the central and southern zone may be due to a decrease in depth of the decollement that steps up from a ductile interface into the brittle/ductile transition.

To the north, a change in structural style from plane-roofed duplexes to hinterland dipping duplexes is suggested. This change results from choices of ramp spacing, relative displacement, and final position of the D2, D3, and M1 duplexes (Fig. 4.13). Figure 4.13 illustrates their relationship as the emplacement of a hanging wall ramp of the D2 duplex (Garhar Ghar in Fig. 4.5) over the footwall flat of moderately north-dipping D3 that is itself emplaced over the footwall ramp of the M1 (next duplex). Thus, Garhar Ghar is an overlap anticline similar to Danda to the south. At Loralai valley, the passive-backthrust emerges over a series of hinterland dipping duplexes (L1, L2, and L3) to form a triangle zone structure (Gordy et al, 1977; Price, 1981).

Thoughts on the deep structure of the hinterland

The space in the cross-section from the northern zone (Fig. 4.11) is filled by hypothetical duplexes using the area-balancing technique (Fig. 4.13). However, I have suggested that the Sulaiman zone is so thick that its basal decollement is essentially at the brittle/ductile transition. If so, the thickness of rock within the ductile zone and above the basement must increase northwards. It is probable that these rocks are tectonically thickened during shortening while the upper part of the system is being removed by erosion. Thus, rocks initially deformed in the ductile zone will gradually occupy portions of the brittle thrust sytem in the hinterland (Fig. 4.18). Mechanisms involved may include: (a) structural thickening of mostly Paleozoic rocks in the lower part of the section by layer-parallel shortening during low grade metamorphism (Moore, 1988; Platt, 1986), or (b) small scale duplexing below the decollement (Moore et al, 1982; Platt et al, 1985). This hypothesis is supported by the observation of widespread small scale ductile folding in the exposed Triassic rocks in the Zhob valley. The ductility of the material in the core zones of Sui and Loti fold from the southern zone also supports this concept.

A preliminary cartoon of how this might work is offered as figure 4.19. In figure 4.19A deformation is just beginning in thick sediments of the continent/ocean transition zone. No attempt has been made to provide realistic geometry to the backstop or plunger of the deformation zone, but a zone at the bottom of the incipient thrust system which is hot enough to be ductile is present. As deformation occurs, flat-and-ramp thrusting develops above the brittle/ductile transition and nearly homogeneous strain shortens and thickens the metamorphosing sediments below the transition. In figure 4.19B, initial deformation and associated surface erosion have occurred. Early-formed duplexes are present in the brittle layer. In addition, a thin wedge of previously-metamorphosed material from the ductile layer has been squeezed up into the base of the brittle zone and is now translated with the duplexes. Molasse sediments fill a foredeep basin in front of the thrust system. In figure 4.19C another increment of thrusting has occurred. More ductile

Figure 4.18. Deep structures of the hinterland? This figure suggests that in the hinterland of the Sulaiman fold belt older rocks may be uplifted due to a wedge of ductilely deformed material. This material initially may have undergone considerable layer-parallel shortening below the decollement at the brittle/ductile boundary. A hypothetical mechanism to explain the development of such a system is illustrated in figure 4.19.

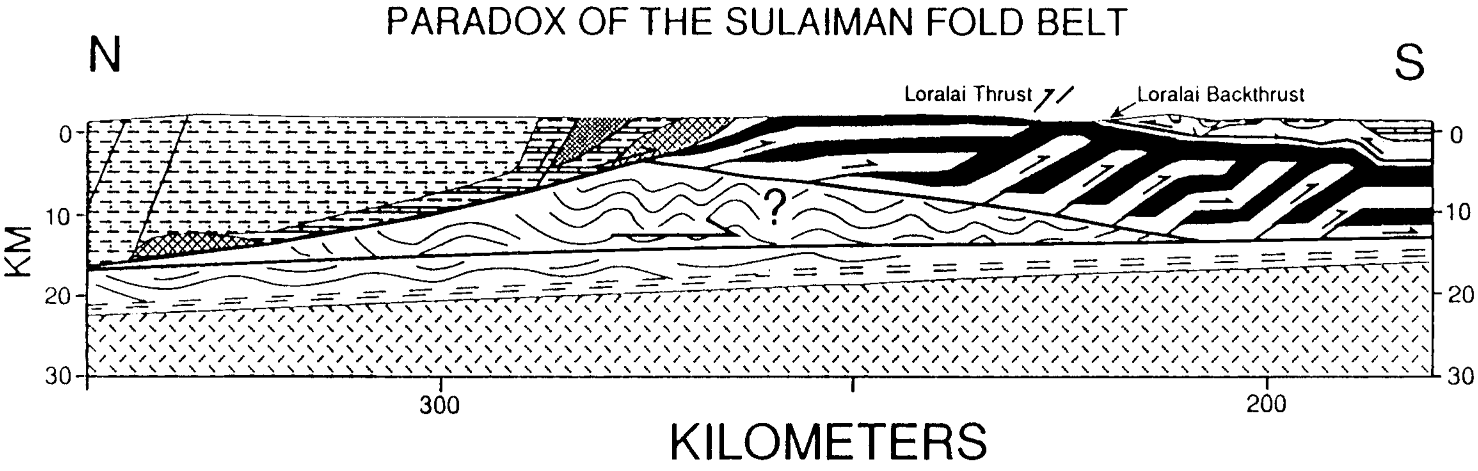

PARADOX OF THE SULAIMAN FOLD BELT
N
S
Loralai Thrust
Loralai Backthrust
?
KM
KM
0
10
20
30
300
200
KILOMETERS

Figure 4.18

Figure 4.19. Hypothetical figure to suggest one mechanism for tectonic thickening and uplift of rocks in the hinterland of the orogenic wedges: A) A subduction complex with sediments about 15 km thick. The system has just started deformating with a decollement at the brittle/ductile interface; B) Deformation with brittle behavior above and ductile behavior below the decollement. The wedge of relatively open dots in figure 4.19A shows the material initially deformed by incipiant metamorphism and thrust over the decollement with increasing shortening in B; C) Another increment of brittle/ductile deformation, uplift and erosion. The mechanism suggests that with increasing shortening the triangle zone will migrate towards the deformation front and metamorphic rocks will get exposed in the hinterland. This mechanism offers a plausible explanation for the exposure of metamorphic rocks in the hinterland of thrust systems and sugggests that new studies of the transition from metamorphic to sedimentary rocks in such systems needs to be re-examined to look for relict brittle/ductile transitions.

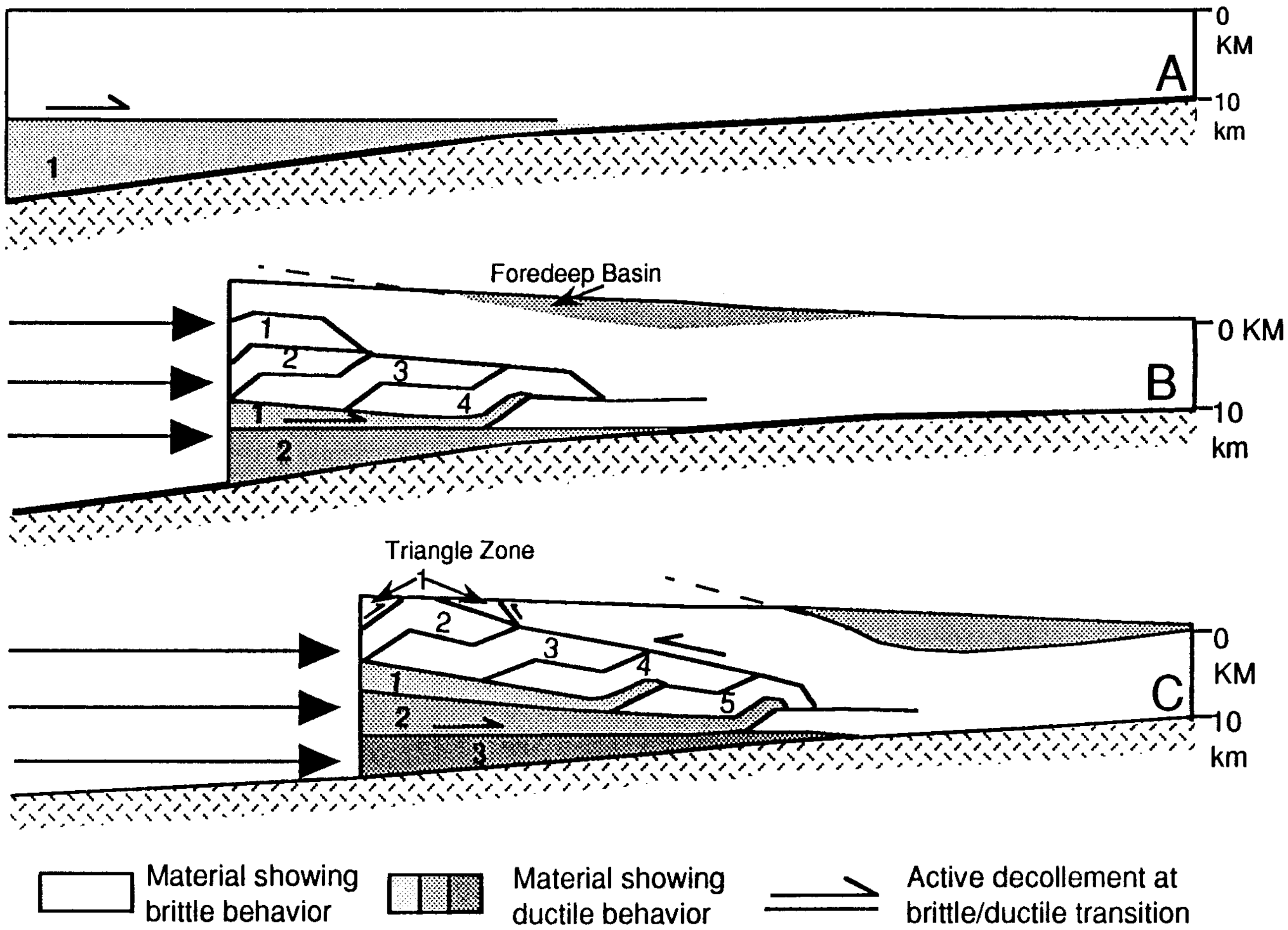

0
KM
A
10
km
1
Foredeep Basin
0 KM
B
10
km
1
2
3
4
1
2
Triangle Zone
1
2
3
4
5
1
2
3
0
KM
C
10
km
Material showing brittle behavior
Material showing ductile behavior
Active decollement at brittle/ductile transition

Figure 4.19

material has lifted into the brittle layer, additional duplexes have developed, and erosion has shifted the foredeep to the south. This process would be expected to continue as long as the sedimentary section is very thick so that the detachment is essentially a metamorphic feature. Note that as more material is added at the base of the hinterland portion of the thrust wedge, the overlying duplexes due to uplift tilt to the south. This is shown in figure 4.18, and is clearly a plausible interpretation of the surface geology used in the hinterland of figure 4.13A. This offers a plausible explanation for the mechanism of exposure of metamorphic rocks in the hinterland of thrust systems and suggests that new studies of the transition from metamorphic to sedimentary rocks in such systems needs to be re-examined to look for relict brittle/ductile transitions.

Evolution of Foreland and Secondary Structures

Initiation of foreland structures

Detailed surface and subsurface observations (Figs. 4.3 & 4.13) of the Sulaiman front allow one to present a detailed analysis of southward propagation of the active Sulaiman fold belt. Sui and Loti are broad, concentric folds which are south of the last foreland duplex, the Pirkoh duplex. I interpret these concentric folds as buckle folds that develop above the ductile material of the detachment horizon. Liu and Dixon (1990) have experimentally modelled similar broad folds preceding faulting. Cooper and Trayner (1986) discuss the propagation of thrust sheets in terms of a ductile bead of deformation ahead of the propagating thrust tip. The southern folds of the Sulaiman belt appear to be a place where this process is now occurring. The small wavelength (about 5 km) Uch frontal fold in the south-western Sulaiman (Figs. 4.2 & 4.20) is actively forming in front of the broad (wavelength > 20 km) concentric Zin (= Loti) fold over the tip of the basal decollement, an incipient fault-propagation fold. I suggest that the broader folds, Sui and Loti/Zin, were initiated by such a structural perturbation which then developed into a full wavelength buckle fold as ductile material flowed from under the synclines into the cores of the anticlines. This shows that broad folding is initiated by a fault-propagation fold due to ductility of material at the detachment horizon. Thus Sui and Loti concentric folds were initiated fault tip line folds. It seems probable that the future evolution of these structures will involve the propagation of a ramp through the core/forelimb of the folds to develop the flat and ramp structures currently seen farther to the north. Thus the Sulaiman provides a clear example of one way that a thrust system propagates into the foreland.

Figure 4.20. Uch fold in the Sulaiman foredeep (See Figs. 4.2 & 4.6 for location). Figure 4.20 A & B shows uninterpreted and interpreted seismic reflection line AW-16-DB shown in figure 4.6. Figure 4.20 C is the depth section to figure 4.20 B and interprets the Uch anticline as a fault-propagation fold. Compare the small wavelength of the Uch fault-propagation fold with the broad wavelength Sui and Loti buckle folds in Figs. 4.2, 4.10, & 4.13). Line AW-16-DB is 8-32 Hz, migrated vibroseis source, recorded and processed by Western Geophysical Company of America in 1973.

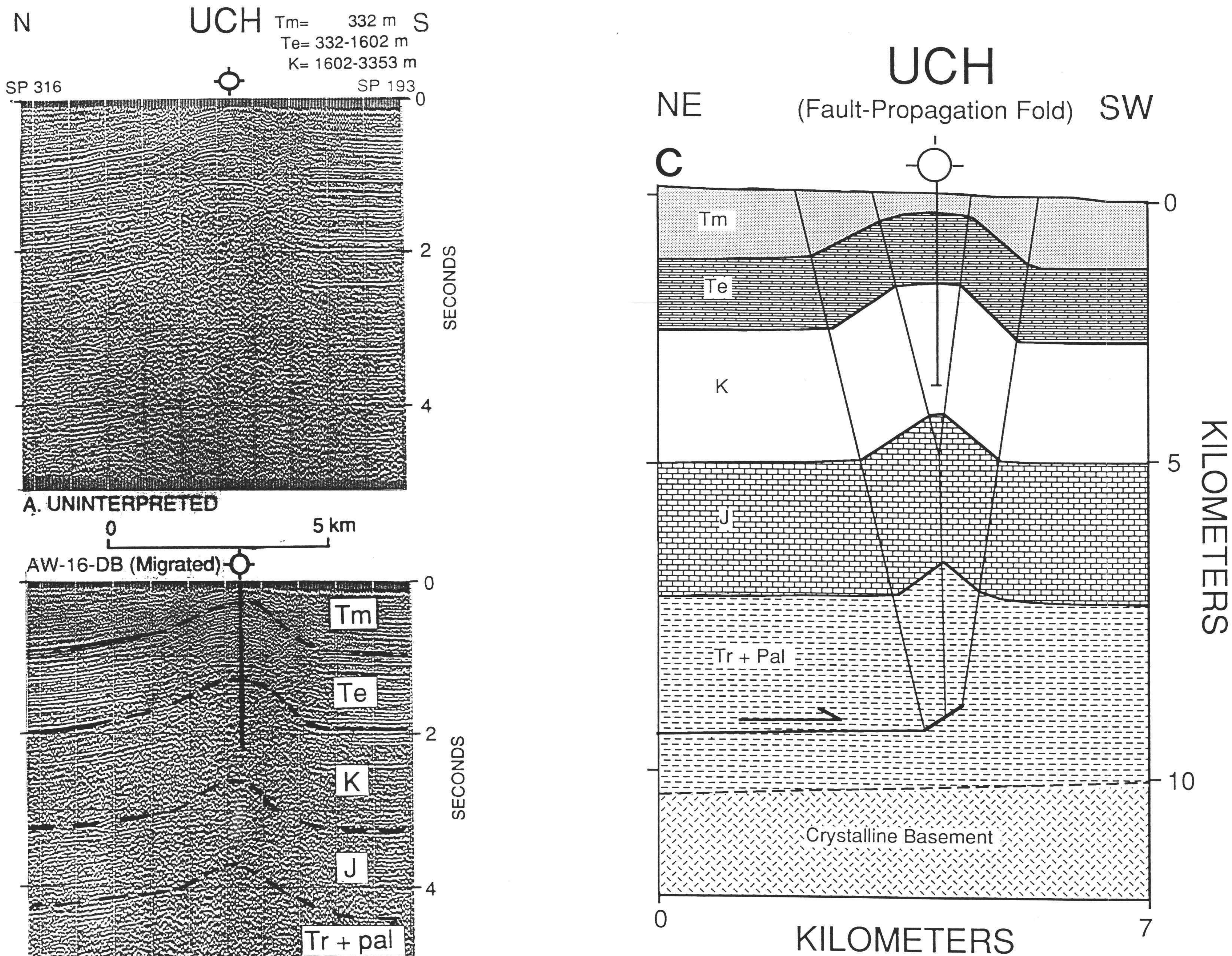

N
UCH
Tm= 332 m
Te= 332-1602 m
K= 1602-3353 m
S
SP 316
SP 193
0
2
4
SECONDS
A. UNINTERPRETED
0
5 km
AW-16-DB (Migrated)
Tm
Te
K
J
Tr + pal
B. INTERPRETED
UCH
NE
(Fault-Propagation Fold)
SW
C
Tm
Te
K
J
Tr + Pal
Crystalline Basement
0
5
10
KILOMETERS
0
7
KILOMETERS

Figure 4.20

Initiation of emergent overstep-backthrusts in long roof sequences

An overstep backthrust is one that emerges from the passive-backthrust (upper detachment). The Mari pop-up zone (Figs. 4.4 & 4.13) occurs just south of the Gumbaz structural depression and can be interpreted as the early stages of development of an emergent overstep-backthrust in this area. This would be the first overstep-backthrust observable in the central Sulaiman lobe as presently configured. Seismic control demonstrates that only the Jandran fault cuts into the duplex sequence, and even it has only small displacement. The area is seismically active, probably at least in part on the Jandran fault. This structure is probably developing in response to the tight Tadri syncline in the passive-roof sequence which apparently locks the passive-backthrust. Secondary thrusting, the pop-ups, probably occurs when increasing strain exceeds the strength of the rocks in the locked roof sequence. I suggest that these secondary faults represent the early stages of development of an overstep-backthrust that may eventually have substantial out-of-sequence displacement (Fig. 4.12). Out-of-sequence structures are commonly interpreted occurring in through the entire duplex wedge (Jaswal, 1990) in order to increase taper and thus driving force. The Mari pop-up structures, as interpreted here, offer an alternative source of out-of-sequence activity in the interior of a thrust system.

Crustal Model

The crustal model developed above (Fig. 4.15D) from the Sulaiman foredeep across eastern Afghanistan (B-B' in Fig. 4.2) has several important implications. The Sulaiman fold belt overlies a broad (>300 km) transitional crust related to the western pre-collisional passive margin of the Indian subcontinent. The about 27 km thick crust in the Sulaiman foredeep thins towards NNE along the cross-section. Transitional crust thins to about 20 km in the hinterland of the Sulaiman fold belt. This interpretation is consistent with S-wave studies of earthquakes (Chun, 1986) and recent Bouguer gravity modelling along an east-west profile from the Sulaiman Range (E-E' in Fig. 4.2; Khurshid, 1991).

Crust closer to oceanic thickness is apparently underthrusting the Afghan block beneath the Chaman fault zone (Fig. 4.15D) as the distal end of the Indian plate crust. When this is considered in the light of the displacement vector calculation done above, I see that the orogenic wedge above the decollement and east of the Chaman fault is mechanically decoupled and behaves as an independent tectonic flake (Oxburg, 1972; Yeats, 1981; Crouch et al, 1984). The Afghan and basement blocks behave relatively rigidly, while transpressional deformation features develop in the Khojak-Sulaiman flake.

Figure 4.21. Comparison of the precollisional margin of the Indian subcontinent (west) with the Blake Plateau Basin of the U.S. Atlantic Margin. Figure 4.21A, shows the restored former western passive margin of the Indian subcontinent in Airy isostatic equilibrium. Densities are the same as in figure 4.15. This broad margin (>300 km wide) with a 20 km thick transitional crust and a thick post-rift sequence is similar to the Blake Plateau Basin of the U.S. Atlantic Margin (Fig. 4.19B, modified from Grow and Sheridan, 1981).

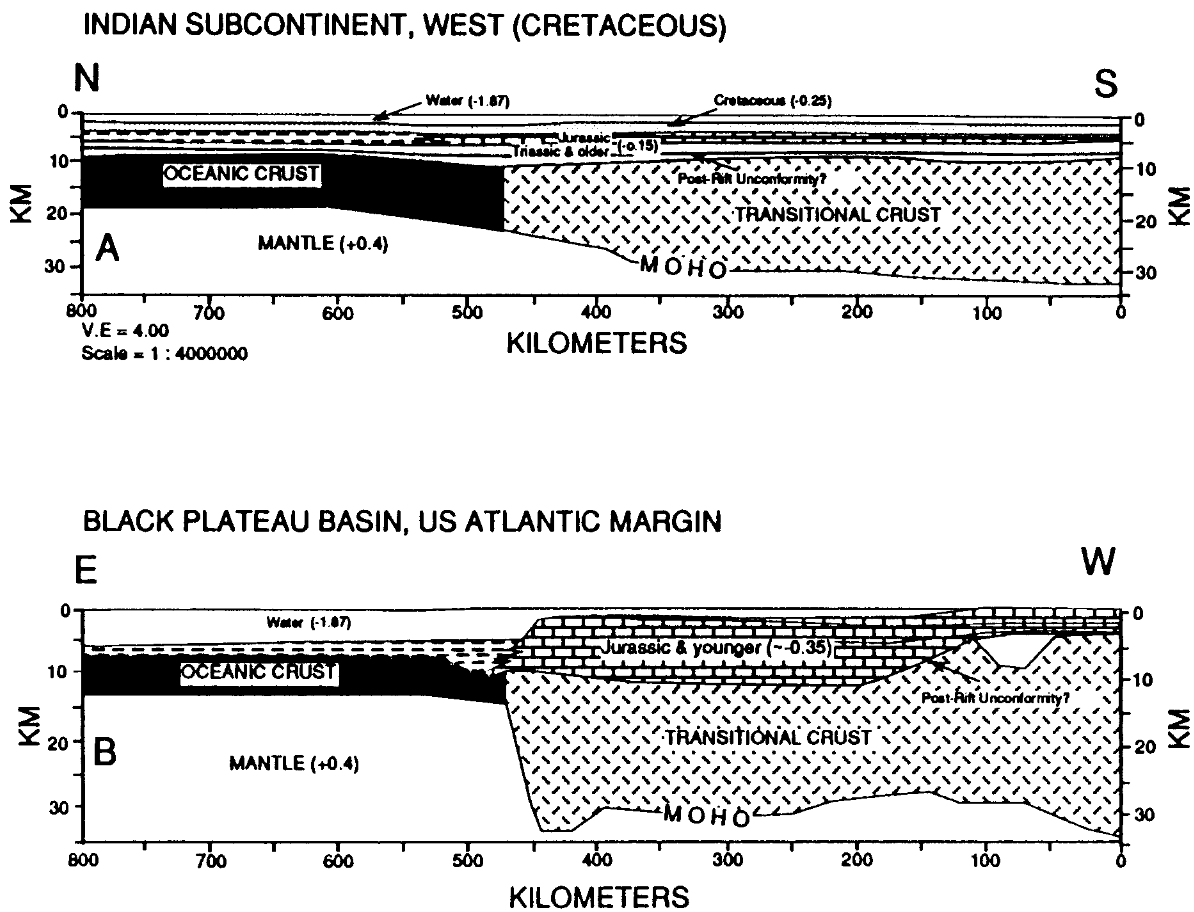

INDIAN SUBCONTINENT, WEST (CRETACEOUS)
N
S
Water (-1.87)
Cretaceous (-0.25)
Jurassic
(-0.15)
Triassic & older
Post-Rift Unconformity?
OCEANIC CRUST
TRANSITIONAL CRUST
A
MANTLE (+0.4)
MOHO
KM
V.E = 4.00
Scale = 1 : 4000000
KILOMETERS
BLACK PLATEAU BASIN, US ATLANTIC MARGIN
E
W
Water (-1.87)
Jurassic & younger (~-0.35)
OCEANIC CRUST
Post-Rift Unconformity?
TRANSITIONAL CRUST
B
MANTLE (+0.4)
MOHO
KM
KILOMETERS

Figure 4.21

The intact transitional crust (20 km) and lack of basement involvement under the Sulaiman fold belt contrast with the full thickness crystalline crust (about 38 km) underneath the Salt Range/Potwar Plateau thrust belt (Duroy et al, 1989) and hineterland basement involvement (Baig, 1990) in northern Pakistan. This suggests an early stage of convergence along the western margin of the Indian subcontinent. My maximum shortening estimate of 378 km in the Sulaiman fold belt (Fig. 4.13) may, therefore, provide a minimum number for any shortening calculated across the collision zone in the Himalaya.

Across the Chaman fault, crystalline crust thickens dramatically to about 57 km in eastern Afghanistan. The model (Fig. 4.15D) suggests that this change in the crustal variation across the Indian-Afghan collision zone may be due to (a) structural thickening within the Afghan block or (b) underplating by oceanic crust of the Indian subcontinent.

Bouguer gravity modelling along B-B' (herein) and E-E' (Khurshid, 1991) in Fig. 4.2 constrains the attitude of the Moho underneath the Sulaiman fold belt. Crustal variation along these sections suggests a dip of 1° toward N57°W to the Moho underneath the Sulaiman fold belt. Seismic and well data discussed above give nearly the same dip direction, but a larger dip of about 3°. Thus the strikes (N33°E) at the top and the base of the north-westwards thinning crystalline basement are about the same. This northeast basement strike underneath the Sulaiman Range suggests that the former passive margin on the western edge of the Indian subcontinent was oriented at almost right angles to the northwest-southeast-trending passive margin involved in the main Himalayan orogeny (Seeber et al, 1981).

Figure 4.21A shows the precollisional (Cretaceous) western passive margin of the Indian subcontinent assuming Airy isostatic equilibrium. Densities used are the same as in Fig. 4.15. Thicknesses of the pre-Cretaceous sediments are from the balanced cross-section (Fig. 4.13B). The former passive margin that developed along the western edge of the Indian subcontinent closely resembles the Blake Plateau Basin of the US Atlantic continental margin (Fig. 4.21B; Grow and Sheridan, 1981; Klitgord et al, 1988; Trehu et al, 1989). Both margins formed as a result of extension have a post-rift platform sequence more than 7 km thick, and a broad (about 350 km) transitional crust with an average thickness of 20 km.

Kinematic Model of Crustal Development, Timing, and Rate of Deformation

An evolutionary diagram beginning in the Jurassic (precollision) models the crustal structures, timing, and rate of deformation across the Indian/Afghan collision zone (Fig. 4.22). In the Jurassic, the Neotethys ocean separated the Afghan block from the Indian subcontinent (Fig. 4.22A). Deformation of the northern Tethys margin started along a northwards subducting slab of Tethys oceanic lithosphere along the south margin of paleo-Asia (Fig. 4.22B). This produced the mid-Cretaceous Kandahar andesitic arc (Lawrence et al, 1981b; Farah et al, 1984; Debon et al, 1986). Deformation of the northwestern margin of the Indian subcontinent, the future Sulaiman area, started by the Paleocene to early Eocene emplacement of the Muslimbagh ophiolites (Allemann, 1979; Otsuki et al, 1989). This event is constrained by the emplacement of ophiolites over Maastrichtian shelf sediments and onlap of Eocene platform rocks (Fig. 4.22C; Allemann, 1979; Otsuki et al, 1989). During the emplacement of the ophiolites, distal, deep-marine facies of Triassic rocks were scraped from the downgoing plate and were transported south-eastwards beneath the translating oceanic lithosphere (Otsuki et al, 1989). Otsuki et al (1989) suggest that these exotic facies which include some basalt flows were deposited near a mid-ocean ridge in relatively shallow water. They may have travelled 200-300 km during the emplacement of the Muslimbagh ophiolite (Otsuki et al, 1989). Deposition of the Khojak flysch occurred on remaining oceanic lithosphere between the Eocene and late Oligocene with the early Himalayan uplift as the most likely sediment source (Lawrence and Khan, 1991a). Continued shortening in the late Oligocene to early Miocene (25±5 Ma?) resulted in the final closure of the ocean, the initiation of the left-lateral strike-slip Chaman fault system, and deformation of the Khojak flysch (Fig. 4.22D; Lawrence and Khan, 1991b). How much shortening occurred during convergence along the Cretaceous subduction zone and the Muslimbagh allochthon is not known. However, the present model based on Bouguer gravity modelling (Fig. 4.22E) shows 57 km of continental crust under eastern Afghanistan. This model predicts a minimum shortening of about 300 km along the fault under the Muslimbagh ophiolites and 200 km overthrusting of the Afghan block over oceanic crust. Shortening in the cover sediments of the Indian subcontinent south of the Muslimbagh ophiolites allochthon probably became significant during the Miocene (20±5 Ma?) with the beginning of deposition of the continental molasse deposits. Since then, 353 ± 25 km of shortening has occurred in the cover sediments of the Indian subcontinent (Fig.

Figure 4.22. Kinematic model inferring the tectonic development across the Indian/Afghan collision zone. A) In Jurassic the Neotethys Ocean separated the Afghan Block from the Indian subcontinent; B) Subduction of the Neotethys and Cretaceous Kandahar andesitic arc volcanism at the leading edge of the Indian subcontinent (Debon et al, 1986); C) Paleocene to early Eocene records the emplacement of Muslimbagh Ophiolites (MBO) over the Cretaceous shelf sediments, onlapped by Eocene limestone (Allemann, 1979); D) Deposition and deformation of Eocene-Miocene Khojak flysch and closure of the ocean basin (Lawrence et al, 1981; Lawrence and Khan, 1991a). Subsequent initiation of left-lateral strike-slip motion along the earlier thrust that becomes the Chaman fault. A little after the development of the Chaman fault todate, 378 km of shortening has occured in the shelf and slope facies of the Indian subcontinent (present day Sulaiman fold belt); E) Present situation.

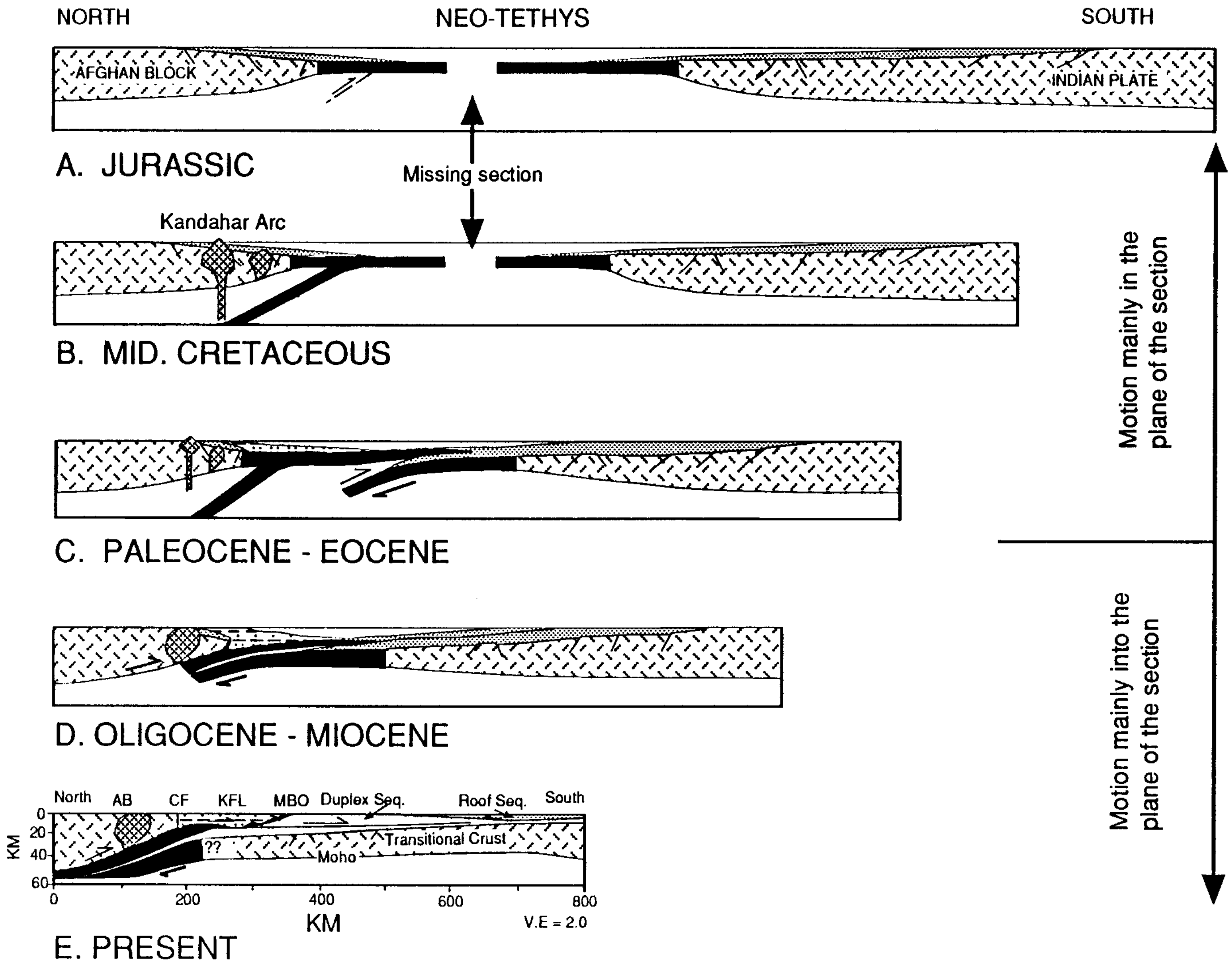

NORTH
NEO-TETHYS
SOUTH
AFGHAN BLOCK
INDIAN PLATE
A. JURASSIC
Missing section
Kandahar Arc
B. MID. CRETACEOUS
C. PALEOCENE - EOCENE
D. OLIGOCENE - MIOCENE
North
AB
CF
KFL
MBO
Duplex Seq.
Roof Seq.
South
KM
0
20
40
60
??
Transitional Crust
Moho
0
200
400
600
800
KM
V.E = 2.0
E. PRESENT
Motion mainly in the plane of the section
Motion mainly into the plane of the section

Figure 4. 22

(4.13). Ongoing prograde deformation consistently reworked the molasse strata so that the center of deposition migrated to the south and east. Presently, active deformation is suggested by recent unconformities from the southern Sulaiman Range (Tainish et al, 1959) and local seismicity. Age dating by magnetostratigraphy (Ahmad and Khan, 1990) shows that continental Siwaliks, deposited between 0.7 Ma to 50,000 yr, are overlain by alluvial fan deposits. The latter are tilted along the eastern Sulaiman front. Shortening estimates in the cover sediments of the Sulaiman fold belt of 353 ±25 km over 20 Ma suggest a shortening rate of about ~18 mm/yr. This number compares with shortening estimates of 9-14 mm/yr in the Salt Range/Potwar Plateau regions (Leathers, 1987; Baker et al, 1988), and 10-15 mm/yr in the sub-Himalaya in India (Lyon-Caen and Molnar., 1985). Further magnetostratigraphic studies in this area should be very productive in providing more refined control on the deformation chronology.

The amount of shortening in the Sulaiman fold belt represents about 50% of the average plate convergence rate of about 37 mm/yr between the Indian subcontinent and the Afghan block almost parallel to the Sulaiman vector determined above (Minster et al, 1974; Minster and Jordan, 1978; Jacob and Quittmeyer, 1979). Continental basement is not found to be involved in the deformation in the Sulaiman fold belt (A-A' in Fig. 4.13). Therefore ductile deformation in metamorphosing basement in the hinterland of the orogen is not yet contributing to shortening. Additional shortening may be accommodated by the left-lateral strike-slip Chaman fault system. Lawrence and Khan (1991b) suggest 450 ± 10 km of left-lateral strike-slip displacement along the Chaman fault over about 25 Ma, for a rate of about 18 mm/yr. If the Chaman vector is resolved into the component parallel to the plate motion vector it is about 15 mm/yr. Thus the sum of the Sulaiman (~18 mm/yr) and Chaman (15 mm/yr) displacement rates of 33 mm/yr is closely comparable to the plate rate of 37 mm/yr.

CONCLUSIONS

Surface and subsurface data have been integrated to evaluate the structural form of the active Sulaiman lobe, the underlying crustal variation, and the total shortening in the cover sediments of the Indian subcontinent and across the Indian/Afghan collision zone. The important conclusions are summarized below.

1. The gentle (<1°) and broad (>300 km) Sulaiman lobe is a thin-skinned feature similar to other fold-and-thrust belts over weak decoupling zones (Davis and Engelder,

1985). In this case the decollement zone may be in fine-grained carbonates buried deep enough to behave ductilely.

2. The style of deformation in the Sulaiman fold belt is a passive-roof duplex geometry with a floor thrust at the base of the wedge and a passive-roof thrust in Cretaceous shales. Two broad (half wavelength about 20 km) folds (Sui and Loti) are located at the southern tip of the decollement zone.

3. A continuous passive-roof sequence is intact for about 150 km northwards from the tip of the first duplex. Eventually it becomes emergent along a passive-backthrust in the Loralai valley, where excess section has been removed by erosion. No other mechanism (e. g., backthrusts, layer parallel shortening, detachment folds, allochthonous roof-sequence, significant deposition after deformation) will adequately account for the major shortening in the extent roof sequence. Surface structures in the southern zone are fault related folds. In the central zone, out-of-sequence structures (secondary foreland and hinterland verging reverse faults with minor throw of <2 km and associated pop-ups) are recognized. Some of them are probably active. They may represent an early stage of evolution of an overstep-backthrust emerging from the upper detachment (passive-backthrust). A structural depression and a triangle zone are the dominant structures of the northern zone. North of the Loralai triangle zone, the duplex style of deformation is replaced by ramp-and-flat geometry. On the Loralai thrust, Jurassic shallow water limestones are overridden by deeper-water, more distal facies. This facies change probably marks the old shelf edge.

4. Structures in the duplex rocks, starting from the foreland to the hinterland (Fig. 4.13) are a fault-bend fold (Pirkoh), overlapping ramp anticline (Danda), intraplate fold (Kurdan), anticlinal stacks (Tadri anticline and Mari pop-up zone), plane-roofed (Gumbaz structural depression), and hinterland dipping duplexes. Farther north the duplex structure is poorly constrained, but is adequately modelled by a simple flat-and-ramp geometry.

5. General chronology of thrusting is as follows: (a) concentric buckle folding at the tip of the decollement; (b) the development of a passive-roof duplex; (c) foreland propagation of the duplex; (d) normal flexural faults at the frontal folds in the roof sequence and tear faults at the margins; and (e) out-of-sequence (secondary) structures towards the hinterland. Existence of secondary structures may explain the active shallow seismicity at the front and in the central parts of the Sulaiman fold belts.

6. The 349 km long balanced structural cross-section from the foreland northwards across the collision zone restores to 727 km. This gives 378 km of maximum shortening in the cover sediments of the Indian subcontinent. Minimum estimate of

shortening. Minimum estimate of shortening is 328 km. This gives an overall shortening of 353±25 km in the cover strata of the Indian subcontinent..

7. Bouguer gravity modelling across the Indian/Afghan collision zone suggests a transitional crust of about 20 km thickness underneath the Sulaiman fold belt related to the passive margin of the Indian subcontinent, and a crystalline crust of about 57 km north of the Chaman fault in Afghanistan. The large crustal thickness in the region of the Afghan block may be due to: (1) structural thickening within crust of the Afghan block; and/or (2) overlap of crust of the lower and upper plate. Oceanic crust distal to the Indian plate extends below the Afghan block to the northwest of the Chaman fault. This implies deformation partitioning with pure translation of the rigid Indian plate below an extensive horizontal decollement, transpression with internal deformation in the thin-skinned brittle wedge above, and buttressing by the relatively rigid Afghan block.

8. The western margin of the Indian subcontinent, trending N33°E, is oriented almost perpendicular to the trend of the main Himalayas (Seeber et al, 1981). The strike of the Moho (N33°E) is consistent with that at the top of the crystalline basement (N33°E) underneath the Sulaiman Range. However, the Moho dips to the northwest with a gentle inclination of about 1° compared to about 3° on the top of the crystalline basement.

The restored western passive margin of the Indian subcontinent has a broad zone (>300 km) of transitional crust about 20 km thick. This is covered by an approximately 7 km thick post-rift sequence. It is similar to the Blake Plateau Basin of the US Atlantic margin.

REFERENCES

Abbas, G. and Z. Ahmad, 1979, The Muslimbagh Ophiolites, in A. Farah and K. A. Dejong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 243-250.

Abdul-Gawad, M., 1971, Wrench movement in the Baluchistan and relation to Himalayan-Indian Ocean Tectonics: GSA Bulletin, v. 82, p. 1235-1250.

Acharyya, S. K., and K. K. Ray, 1982, Hydrocarbon possibilities of concealed Mesozoic-Paleogene sediments below Himalayan nappes, reappraisal: AAPG Bulletin, v. 66, p. 57-70.

Ahmad, W., and M. J. Khan, 1990, Sedimentologic and magnetostratigraphic studies of the Upper Siwalik Group, Sulaiman Range, Pakistan: Second Pakistan Geologic Congress, Abstracts with program, Department of Geology, University of Peshawar, Pakistan, p. 33-34.

Ahmed, I., and R. McElroy, 1991, Thrust Kinematics in the Kohat Plateau, Trans Indus Range, Pakistan: Journal of Structural Geology, v. 13, p. 319-327.

Allemann, F., 1979, Time of emplacement of the Zhob valley ophiolites and Bela ophiolites, in A. Farah and K. A. Dejong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 215-242.

Andritzky, G., et al, 1973, Geological map of central and southern Afghanistan: Bundsanstalt fur Bodenforschung, West Germany.

Asrarullah, Z. Ahmad, and S. G. Abbas, 1979, Ophiolites in Pakistan: an introduction, in A. Farah and K. A. Dejong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 181-192.

Auden, J. B., 1974, Afghanistan-Pakistan, in Mesozoic-Cenozoic orogenic belts: Data for orogenic studies, in A. M. Spencer, eds., Geological Society of London, Special Publication, v. 4, p. 235-253.

Bachmann, G. H., G. Dohr, and M. Muller, 1982, Exploration in a classic thrust belt and its foreland: Bavarian Alps Germany: AAPG Bulletin, v. 66, 2529-2542.

Baig, M. S., 1990, Structure and Geochronology of pre-Himalayan and Himalayan orogenic events in the northwest Himalaya, Pakistan, with special reference of the Besham area: Ph.D thesis, Department of Geosciences, Oregon State University, Corvallis, Oregon, 397 p.

Baker, D. M., R. J. Lillie, R. S. Yeats, G. D. Johnson, M. Yousaf, and A. S. H. Zaman, 1988, Developmentof the Himalayan thrust zone: Salt Range, Pakistan: Geology, v. 16, p. 3-7.

Bally, A. W., P. L. Gordy, and G. A. Stewart, 1966, Structure, seismic data, and orogenic evolution of southern Canadian Rocky Mountains: Bulletin of the Canadian Petroleum Society, V. 14, p. 337-381.

Banks, C. J., and J. Warburton, 1986, `Passive-roof' duplex geometry in the frontal structures of the Kirthar and Sulaiman mountain belt, Pakistan: Journal of Structural Geology, v. 8, p. 229-237.

Bannert, D., and A. Cheema, 1979, Interpretation of Landsat-MSS Imagery of the Sulaiman and Kirthar Mountain Ranges in western Pakistan: A technical report of a cooperative project between Bundesanstalt fur Geowissenschaften und Rohstoffe, Hannover, West Germany and Hydrocarbon Development Institute of Pakistan, Project # 83.2068.1, 49 p.

Berg, T, M. et al., 1980, Geologic map of Pennsylvania: Pennsylvania Department of Environmental Resources, Topographic and Geological Survey, 2 sheets, scale 1:2,500,000.

Bhatti, A., J. M. Mengal, M. Ahmad, and M. K. Pasha, 1984, Geological maps of Anambar and Gumbaz: Geological Survey of Pakistan, sheet # 39B/16 (2 sheets), scale 1: 25,000.

Bordet, P., 1978, The western border of the Indian plate: implications for Himalayan geology, Tectonophysics, v. 51, p. T71-T76.

Boulin, J., 1981, Afghanistan structure, greater India concept, and eastern Tethys evolution: Tectonophysics, v. 72, p. 261-287.

Boyer, S. E., and D. Elliot, 1982, Thrust Systems: AAPG Bulletin, v. 66, p. 1196-1230.

___ 1986, Styles of folding within thrust sheets: Examples from the Appalachian and Rocky Mountains of the U.S.A. and Canada: Journal of Structural Geology, v. 8, p. 325-340.

Butler, R. W. H., 1982, The terminology of structures in thrust belts: Journal of Structural Geology, v. 4, p. 239-245.

Chandra, U., 1981, Focal mechanism solutions and their tectonic implications for the eastern Alpine-Himalayan region, In H. K. Gupta and F. Delany, eds., Zagros, Hindukush, Himalaya, Geodynamic Evolution, p. 243-271.

Chun, Kin-Yip., and Yoshii, 1977, Crustal structure of the Tibet Plateau: a surface wave study by moving window analysis, Bulletin Seismological Society of America, v. 67, p. 735-750.

___1986, Crustal block of the western Ganga Basin: A fragment of oceanic affinity: Bulletin Seismological Society of America, v. 76, p. 1687-1698.

Cooper, M. A., and P. M. Trayner, 1986, Thrust-surface geometry: implications for thrust-belt evolution and section balancing techniques: Journal of Structural Geology, v. 8, p. 305-312.

Coward, M. P., and R. W. H. Butler, 1985, Thrust tectonics and deep structures of the Pakistan Himalayas: Geology, v. 13, p. 417-420.

Crouch, J. K., S. B. Bachman, and J. T. Shay, 1984, Post-Miocene compressional tectonics along the central California margin, in J. K. Crouch and S. B. Bachman, eds., Tectonics and Sedimentation Along the California Margin: Pacific Section, v. 38, p. 37-54.

Dahlstrom, C. D. A., 1969a, Balanced cross-sections: Canadian Journal of Earth Science, v. 6, p. 743-757.

___ 1969b, The upper detachment in concentric folding: Bulletin of Canadian Petroleum Geology, v. 17, p. 326-346.

___ 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, p. 332-406.

Davis, D., J. Suppe, and F. A. Dahlen, 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, p. 1153-1172.

___ and T. Engelder, 1985, The role of salt in fold-and-thrust belts: Tectonophysics, v. 119, p. 67-88.

Debon, F., H. Afzali, P. Le Fort, and J. Sonet, 1986, Plutonic belts in Afghanistan: Typology, Age, and Geodynamic setting: Sciences de la Terre, Memoire 47, p. 129-153.

DeJong, K. A., and A. M. Subhani, 1979, Notes on the Bela ophiolites with special reference to the Kanar area, in A. Farah and K. A. Dejong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 263-270.

Duroy, Y., A. Farah, and R. J. Lillie, 1989, Subsurface densities and lithospheric flexure of the Himalayan foreland in Pakistan, in L. L. Malinconico and R. J. Lillie, eds., Tectonics of the western Himalayas: GSA Special Paper 232, p. 217-236.

Elliot, D., and M. R. W. Johnson, 1980, Structural evolution in the northern part of the Moine thrust belt, NW Scotland: Royal Society of Edenburg Transaction, v. 71, part 2, p. 69-96.

___ 1982, The construction of balanced cross-sections: Journal of Structural Geology, v. 5, p. 101.

Farah, A., and N. A. Zaigham, 1979, Gravity anomalies of the ophiolite complex of the Khanozai, Muslimbagh-Qila Saifullah area, Zhob District, Baluchistan, in A. Farah and K. A. Dejong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 251-262.

___ G. Abbas, K. A. DeJong, and R. D. Lawrence, 1984. Evolution of the lithosphere in Pakistan: Tectonophysics, v. 105, p. 207- 227.

Gansser, A., 1979, Reconnaissance visit to the ophiolites in Baluchistan and the Himalaya, in A. Farah and K. A. Dejong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 193-214.

___ 1981, The geodynamic history of the Himalaya, in: H. K. Gupta and F. Delany, eds., Zagros, Hindu Kush, Himalaya: Geodynamic evolution, American Geophysical Union, Geodynamic Series, v. 3, p. 111-121.

Geiser, P. A., 1988a, Mechanism of thrust propagation: some examples and implications for the analysis of overthrust terranes: Journal of Structural Geology, v. 10, p. 829-845.

___1988b, The role of kinematics in the construction and analysis of geological cross sections in deformed terranes, in G. Mitra and S. Wojtal, eds., Geometries and mechanisms of thrusting with special reference to the Appalachians: GSA Special paper 222, p. 47-76.

Gordy, P. L., F. R. Frey., and D. K. Norris, 1977, Geological guide for the C.S.P.G and 1977 Waterton-Glacier Park Field conference: Canadian Society of Petroleum Geologist, Calgary.

Grow, J. A., and R. E. Sheridan, 1981, Deep structure and evolution of the continental margin off the United States: Oceanologica Acta, Geology of continental margins symposium, Paris, July 7-17, p. 11-19.

Groshong, R. H., and S. I. Usdansky, 1988, Kinematic model of plane-roofed duplex styles, in G. Mitra and S. Wojtal, eds., Geometries and mechanisms of thrusting with special reference to the Appalachians: GSA Special paper 222, p. 197-206.

Gwinn, V. E., 1970, Kinematic patterns and estimates of lateral shortening, Valley and Ridge and Great Valley Provinces, central Appalachians, south-central Pennsylvania, in: G. W. Fisher et al., eds., Studies in Appalachian Geology, Central and Southern: Interscience, New York, p. 127-146.

Gupta, H. K., and H. Narain, 1967, Crustal structure of the Himalayan and the Tibet Plateau regions from surface wave dispersion: Bulletin Seismological Society of America, v. 57, p. 235-248.

Hall, A., 1987, Igneous petrology: John Wiley & Sons Inc., New York, 573 p.

Harris, L. D., and R. C. Milici, 1977, Characteristics of thin-skinned style of deformation in the southern Appalachians and potential hydrocarbon traps: USGS Professional Paper 1018, 40 p.

Herman, G. C., 1984, A structural analysis of a portion of the valley and ridge Province of Pennsylvania: Master's thesis, University of Connecticut, 107 p.

Hobson, D. M., 1986, A thin skinned model for the Papuan thrust belt and some implications for hydrocarbon exploration: Australian Petroleum Exploration Association Journal, v. 26, p. 214-224.

Hossack, J. R., L. Deramond, and R. H. Graham, 1984, The geological structure and development of the Pyrenees: Toulouse Conference on Thrusting and Deformation, Abstracts of Programs, p. 46-47.

Humayon, M., R. J. Lillie, and R. D. Lawrence, 1991, Structural interpretation of eastern Sulaiman foldbelt and foredeep, Pakistan: Tectonics, v. 10, p. 299-324.

Hunting Survey Corporation, 1961, Reconnaissance Geology of part of West Pakistan: A Columbo Plan Cooperative Project. Government of Canada, Geodynamic, Toronto, 550 p.

Iqbal, M. W. A., and S. M. I. Shah, 1980. Records of the geological survey of Pakistan: A guide to the stratigraphy of Pakistan: 37 p.

Izatt, C. N., 1990, Variation in thrust front geometry across the Potwar Plateau and Hazara/Kalachitta hill ranges, northern Pakistan: Ph.D thesis, Department of Geology, Imperial College of Science Technology and Medicine, University of London, 353 p.

Jackson, J. A., 1980, Reactivation of basement faults and crustal shortening in orogenic belts: Nature, v. 283, p. 343-346.

Jacob, K. H., and R. C. Quittmeyer, R.C. 1979, The Makran region of Pakistan and Iran: trench-arc system with active plate subduction, in A. Farah and K. A. DeJong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 305-318.

Jadoon, I. A. K., R. J. Lillie, M. Humayon, R. D. Lawrence, S. M. Ali, and A. Cheema, 1989, Mechanism of deformation and the nature of the crust underneath the Himalayan foreland fold-and-thrust belts in Pakistan: EOS, Transaction, American Geophysical Union, v. 70, p. 1372-1373.

___A. Khurshid, and R. J. Lillie, 1990a, Crustal variation across the western margin of the Indian subcontinent in Pakistan and eastern Afghanistan: GSA Abstracts with Ptogram, v. 22, p. 205.

___and S. H. Khan, 1990b, Pop-up structures in the central Sulaiman fold belt of Pakistan: EOS, Transaction, American Geophysical Union, v. 71, p. 1592.

___R. D. Lawrence, and R. J. Lillie, 1991, Balanced and retrodeformed geological cross-section from the frontal Sulaiman Lobe, Pakistan: Duplex development in thick strata along the western margin of the Indian plate, in K. McClay, eds., Thrust Tectonics: in press, Unwin Hyman, London.

Jaswal, T., R. J. Lillie, and R. D. Lawrence, 1991, Structure and evolution of the Durnal oil field, Nothern Potwar Deformed Zone, Pakistan: AAPG Bulletin (submitted).

Jaume, S. C. and R. J. Lillie, 1988, Mechanics of the Salt Range-Potwar Plateau, Pakistan: A fold and thrust belt underlain by evaporites: Tectonics, v. 7, p. 57-71.

Johnson, N. M., N. D. Opdyke, G. D. Johnson, E. H. Lindsay, and R. A. K. Tahirkheli, 1982, Magnetic polarity stratigraphy and ages of the Siwalik Group rocks of the Potwar Plateau, Pakistan: Paleogeography, Paleoclimatcology, Paleoecology, v. 37, p. 17-42.

___J. Stix, L. Tauxe, P. F. Cerveny, and R. A. K. Tahirkheli, 1985, Paleoclimatic chronology, fluvial processses, and tectonic implication of the Siwalik deposits near Chinji Village, Pakistan: Journal of Geology, v. 93, p. 27-40.

Jones, P. B., 1982, Oil and gas beneath east-dipping thrust faults in the Alberta Foothills. in K.Powers, eds., Rocky Mountain Association of Geologists Guidebook, v. 1, p. 61-74.

___1987, Quantitative geometry of thrust and fold belt structures: AAPG Methods in Exploration Series, 6, 26 p.

Kaila, K. L., 1981, Structure and seismotectonics of the Himalaya-Pamir-Hindukush Region and the Indian plate boundary, in H. K. Gupta and F. Delany, eds., Zagros, Hindu Kush, Himalaya, Geodynamic evolution: American Geophysical Union, Geodynamic Series, v. 3, p. 272-293.

Kamran, M., and U. Ranki, 1987, Pakistan well data: Hydrocarbon Development Institute of Pakistan, unpublished report, 128 p.

Khan, M. A., and H. A. Raza, 1986, The role of geothermal gradients in hydrocarbon exploration in Pakistan: Journal of Petroleum Geology, v. 9, p. 245-258.

Kazmi, A. H., 1979, Active fault systems in Pakistan, in A. Farah and K. A. Dejong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 285-294.

___1981, Stratigraphy and sedimentation of the Jurassic in north-eastern Baluchistan: Geological Bulletin, University of Peshawar, v. 14, p. 193-198.

___and R. A. Rana, 1982, Tectonic map of Pakistan, 1:2,000,000. Geological Survey of Pakistan, Quetta.

Khurshid, A., 1991, Crustal structure of the Sulaiman Range, Pakistan from gravity data: Master's thesis, Department of Geosciences, Oregon State University, Corvallis, Oregon, 56 p.

Klitgord, K. D., D. R. Hutchinson, and H. Schouten, 1988, U.S. Atlantic continental margin; Structural and tectonic framwork, in R. E. Sheridan and J. A. Grow, eds., Atlantic continental margin, U.S.: GSA, The Geology of North America, v. I-2, p, 19-53.

Klootwijk, C. T., R. Naziz-Ullah, K. A. DeJong, and A. Ahmad, 1981, A paleomagnetic reconaissance of northern Baluchistan, Pakistan: Journal of Geophysical Research, v. 86, p. 289-305.

___ P. J. Conaghan, and C. M. Powell, 1985, The Himalayan Arc; large-scale continental subduction, oroclinal bending, and back-arc spreading: Geologische Rundschan, v. 67, p. 37-48.

Laubscher, H. P., 1981, The 3D propagation of decollement in the Jura, in K. R. McClay and N. J. Price. eds., Thrust and Nappe Tectonics: Geological Society of London, Special Publication 9, p. 311-318.

Lawrence, R. D., S. H. Khan, K. A. Dejong, A. Farah, and R. S. Yeats, 1981a, Thrust and strike-slip fault interaction along the Chaman fault zone, Pakistan, in K. R. McClay and N. J. Price, eds., Thrust and Nappe Tectonics: Geological Society of London, Special Publication 9, p. 363-370.

___ R. S Yeats, S. H. Khan, A. M. Subhani, and D. Bonelli, 1981b, Crystalline rocks of the Spinatizha area, Pakistan: Journal of Structural Geology, v. 3, p. 449-457.

___ et al., 1989, Tectonics south of the suture: GSA Abstracts (28th International Geological Conference, p. 265.

___ and S. H. Khan, 1991a, Structural reconnaissance of Khojak flysch, Pakistan and Afghanistan.

___ and ___ 1991b, Chaman fault, Pakistan, Afghanistan.

Leathers, M., 1987, Balanced structural cross-section of the western Salt Range and Potwar Plateau: deformation near the strike-slip terminous of an overthrust sheet: Master's thesis, Oregon State University, Corvallis, Oregon, 271 p.

Le Fort, P. 1975, Himalayas: the collided Range. Present knowledge of the continental arc: American Journal of Science, v. 275, p. 1-44.

Lillie, R. J., and M. Yousaf, 1986, Modern analogs for some midcrustal reflections observed beneath collisional mountain belts: in M.Barazangi and L. Brown, eds., Reflection Seismology: The Continental Crust: American Geophysical Union, Geodynamic Series, v. 14, p. 55-65.

___ G. D. Johnson, M. Yousaf, A. S. H. Zamin, and R. S. Yeats, 1987, Structural development within the Himalayan foreland fold-and-thrust belt of Pakistan, in C. Beaumont and A. J. Tankand, eds., Sedimentary basins and basin-forming mechanisms: Canadian Society of Petroleum Geologist, Memoir 12, p. 379-392.

___ R. D. Lawrence, M. Humayon, and I. A. K. Jadoon, 1989, The Sulaiman thrust Lobe of Pakistan: Early stage underthrusting of the Mesozoic rifted margin of the Indian subcontinent: GSA Abstracts with Program, p. 318.

___ D. M. Davis, 1990, Structure and mechanics of the foldbelts of Pakistan: Thrust Tectonics (Conference), University of London, Abstracts with program, p. 69.

___ 1991, Evolution of gravity anomalies across collisional mountain belts: clues to the amount of continental convergence and underthrusting: Tectonics (in press).

Liu, S., and J. M. Dixon, 1990, Localization of thrust ramp by buckling: Analog and numerical models: GSA Abstract with program, p. 141.

Lyon-Caen, H., P. Molnar, 1983, Constraints on the structure of the Himalaya from an analysis of gravity anomalies and a flexure model of the lithosphere: Journal of Geophysical Research, v. 88, p. 8171-8191.

Malinconico, L. L., 1989, Crustal thickness estimates for western Himalayas, in L. L. Malinconico and R. J. Lillie, eds., Tectonics of the western Himalayas: GSA Special paper 232, p. 237-242.

Marussi, A., 1976, Introductory report of geophysics, in Geotectonica Delle Zone Orogeniche Del Kashmir Himalaya, Karakoram-Hindukush-Pamir: Accademia Dei Lincei, v. 21, p. 15-25.

Mattauer, M., 1986, Intracontinental subduction, crust-mantle decollement and crustal stacking wedge in the Himalayas and other collision belts, in M. P. Coward and A. C. Ries eds., Collision Tectonics: Special Publication of the Geological Society, London, v. 19, p. 37-50.

McDougall, J, 1989, Geology and Geophysics of the foreland fold-thrust belt of northwestern Pakistan: Ph.D thesis, Oregon State University, Corvallis, Oregon, U.S.A, 140p.

___and S. H. Khan, 1990, Strike-slip faulting in a foreland fold-thrust belt: The Kalabagh fault and western Salt Range, Pakistan: Tectonics, v. 9, p. 1061-1076.

___ and A. Hussain, 1991, Fold and Thrust Propagation in the western Himalaya based on a balanced cross-section of the Surghar Range and Kohat Plateau, Pakistan: AAPG Bulletin, v. 75, p. 463-478.

McGinnis, L. D., 1971, Gravity field and tectonics in the Hindukush: Journal of Geophysical Research, v. 76, p. 1894-1904.

Menke, W. H., and K. H. Jacob, 1976, Seismicity pattern in Pakistan and northwestern India associated with continental collision: Seismological Society of America Bulletin, v. 66, p. 1695-1711.

Minster, J.B., T. H. Jordan, P. Molnar, and E. Haines, 1974, Numerical modelling of instantaneous plate tectonics: Royal Astronomical Society Geophysics Journal., v. 36, p. 541-576.

Minster, J. B., and T. H., Jordan, 1978, Present day plate motions: Journal of Geophysical Research, v. 83, p. 5331-5354.

Mitra, S., 1986, Duplex structures and imbricate thrust systems: Geometry, structural position, and hydrocarbon potential: AAPG Bulletin, v. 70, p. 1087-1112.

___ 1987, Regional variations in deformation mechanisms and structural styles in the central Appalachian orogenic belt: GSA Bulletin, v. 98, p. 569-590.

Molnar, P., 1984, Structure and tectonics of the Himalaya: Constraints and implications of Geophysical data: Annual review of the Earth and Planetary Science, v. 12, p. 489-518.

Morley, C. K., 1986, A classification of thrust fronts: AAPG Bulletin, v. 70, p. 12-25.

___ 1988, Out-of-sequence thrusts: Tectonics, v. 7, p. 539-561.

Moore, J. C., et al., 1982, Offscrapping and underthrusting of sediments at the deformation front of the Barbados ridge: Deep sea drilling project leg 78A, GSA Bulletin, v. 93, p. 1065-1077.

___1989, Tectonics and hydrogeology of accretionary prisms: role of the decollement zone: Journal of Structural Geology, v. , p. 95-106.

Nakata, T., Active faults map of Pakistan, scale 1: 2,000,000 (in preparation).

Otsuki, K., M. Anwar, J. M. Mengal, I. A. Brohi, K. Hohino, A. N Fatmi, and Y. Okimura, 1989, Muslimbagh area of Baluchistan: Geological Bulletin, University of Peshawar, v. 22, p. 103-126.

Oxburgh, E. R., 1972, Flake tectonics and continental collision: Nature, v. 239, p. 202-204.

Platt, J. P., L. K. Leggett, J. Young, H. Raza, and S. Alam, 1985, Large scale sediment underplating in the Makran accretionary prism: Geology, v. 13. p. 507-511.

___ 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: GSA Bulletin, v. 97, p. 1037-1053.

Perry, W. J., 1978, Sequential deformation in the central Appalachian: American Journal of Science, v. 278, p. 518-542.

Patriat, P., and J. Achache, 1984, Collision chronology and its implications for crustal shortening and the driving mechanisms of plates, India-Eurasia: Nature, v. 311, p. 615-625.

Pennock, E, S., R. J. Lillie, A. S. H. Zaman, and M. Yousaf, 1989, Structural interpretation of the seismic reflection data from eastern Salt Range and Potwar Plateau, Pakistan: AAPG Bulletin, v. 73, p. 841-857.

Powell, C. M. A., 1979, A speculative tectonic history of Pakistan and surroundings: Some constraints from Indian Ocean: in A. Farah and K. A. DeJong, Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 5-24.

Price, R. A., 1981, The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains, in K. R. McClay, and N. J. Price, eds., Thrust and Nappe Tectonics: Special Publication of Geological Society of London, v. 9, p. 427-448.

__ 1986, The southeastern Canadian Cordillera: thrust faulting, tectonic wedging, and delamination of the lithosphere: Journal of Structural Geology, v. 8, p. 239-254.

Quadri, V. N., and M. Shuaib, 1986, Hydrocarbon prospects of southern Indus basin: AAPG Bulletin, v. 70, p. 730-747.

Quittmeyer, R. C., A. Farah, and K. H. Jacob, 1979, The seismicity of Pakistan and its relation to surface faults, in A. Farah and K. A. DeJong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 351-358.

___A. A. Kaffa, and J. G. Armbruster, 1984, Focal mechanism and depths of earthquakes in Central Pakistan: A tectonic interpretation: Journal of Geophysical Research, v. 89, p. 2459-2470.

Raiverman, V., S. V. Kunte, and A. Mudherjea, 1983, Basin geometry, Cenozoic sedimentation, and hydrocarbon prospects in northwestern Himalaya and Indo-Gangetic plains: Petroleum Asia Journal, v. 6, v. 67-92.

Raynolds, R. G. H., and G. D. Johnson, 1985, Rates of Neogene depositional and deformational processes, northwest Himalayan foredeep margin, Pakistan. The chronology of the Geological Records, in N. J. Snelling, eds., Geological Society of London, Memoir 10, p. 297-311.

Rahman, A., 1969, Crustal section across the Sibi-Syntaxial Bend, West Pakistan, Based on gravity measurements: Journal of Geophysical Research, v. 74, p. 4367-4370.

Raza, H. A., R. Ahmed, S. Alam, and S. M. Ali, 1989a, Petroleum Prospects: Sulaiman Sub-Basin, Pakistan: Pakistan Journal of Hydrocarbon Research, v. 1, # 2, p. 21-56.

___R. Ahmad, S. Alam, and S. M. Ali., 1989b, Petroleum zones of Pakistan: Pakistan Journal of Hydrocarbon Research, v. 1, # 2, p. 1-20.

Rich, J. L. 1934, Mechanics of low-angle overthrust faulting as illustrated by the Cumberland thrust block, Virginia, Kentucky, Tennessee: AAPG Bulletin, v. 18, p. 1584-1596.

Roeder, D., O. E. Gilbert Jr, and M. D. Witherspoon, 1978, Evolution and macroscopic structure of Valley and Ridge Province thrust belt; Tennessee and Virginia: Knoxville, University of Tennessee, Department of Geological Sciences, Studies in Geology, v. 2, 25 p.

Rowlands, D.,1978, The structure and seismicity of a portion of southern Sulaiman Ranges, Pakistan: Tectonophysics, v. 51, 41-56.

Sarwar, G., and K. A. DeJong, 1979, Arcs, oroclines, syntaxes: The curvature of mountain belts in Pakistan, in A. Farah and K. A. DeJong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 351-358.

Searle, M. P., 1986, Structural evolution and sequence of thrusting in the High Himalayan, Tibetan-Tethys and Indus suture zones of Zanskar and Ladakh, western Himalaya: Journal of Structural Geology, v. 8, p. 923-936.

___ B. F. Windley, M. P. Coward, V. Thakur, S. Kumar, and M. Jan, 1987, The closing of Tethys and the tectonics of the Himalaya: GSA Bulletin, v. 98, p. 678-701.

Seeber, L., J. Armbruster, 1979, Seismicity of Hazara Arc in northern Pakistan: synthesis and interpretation of recent data at plate scale, in A. Farah and K. A. DeJong, eds., Geodynamics of Pakistan: Geological Survey of Pakistan, Quetta, p. 131-142.

___J. G. Armbruster, and R. C. Quittmeyer, 1981, Seismicity and continental subduction in the Himalayan Arc, in H. K. Gupta and F. M. Delany, eds., Zagros, Hindukush, Himalaya; geodynamic evolution, American Geophysical Union Geodynamic Series, v. 3, p. 215-242.

Sheriff, R. E., 1984, Encyclopedic dictionary of exploration geophysics, 2nd ed: Society of exploration geophysicists, 323 p.

Suppe, J., 1980, Imbricated structure of western foothills belt, south central Taiwan: Petroleum Geology of Taiwan, v. 17, p. 1-16.

___ 1983, Geometry and kinematics of fault bend folding: American Journal of Science, v. 283, p. 684-721.

Tahirkheli, R. A. K., and Q. Jan, 1979, Geology of Kohistan, Karakoram, Himalaya, northern Pakistan: Special issue of the Geological Bulletin of the University of Peshawar, Pakistan, v. 11, p. 1-30.

Tainsh, H. R., K. V. Stringer, and J. Azad, 1959, Major gas fields of west Pakistan: AAPG Bulletin, v. 43, p. 2675-2700.

Tapponnier, P., M. Mattauer, F. Proust, and C. Cassaigneau, 1981, Mesozoic ophiolites, sutures, and large-scale movements in Afghanistan, Earth and Planetary Science Letters, v. 52, p. 355-371.

___G. Peltzer, A. Y. Ledain, R. Armijo, and P. Cobbold, 1982, Propagating extrusion tectonics in Asia: New insights from simple experiments with plasticene: Geology, v. 10, p. 611-616.

Thompson, R. I., 1979, A structural interpretation across a part of the northern Rocky Mountains, British Columbia, Canada: Canadian Journal of Earth Science, v. 16, p. 1228-1241.

Trehu, A. M., K. D. Klitgord, D. S. Sawyer, and R. T. Buffler, 1989, Atlantic and Gulf of Mexico continental margin, in L. C. Pakiser and W. D. Mooney, Geophysical framwork of the continental United States: GSA Memoir 172, p. 349-382.

Vann, I. R., R. H. Graham, and A. B. Hayward, 1986, The structure of mountain fronts: Journal of Structural Geology, v. 8, p. 215-227.

Waheed, A., N. A. Wells, N. Ahmad, and K. D. Tabutt, 1988. Paleocurrents along an obliquely convergent plate boundary, Sulaiman fold belt, south west Himalayas, West central Pakistan: AAPG Bulletin Abstracts with Program, v. 72, p. 255-256.

Wallace, W. K., 1990, Detachment folds over a passive-roof duplex: An example from the northeastern Brooks Range, Alaska: Thrust Tectonics, University of London, Abstracts with program, p. 41.

Wittekindt, H., and D. Weippert, 1973, Geological map, central southern Afghanistan: Geological Survey, Federal Republic of Germany, Hannover and Kabul.

Woodward, N. B., S. E. Boyer, and J. Suppe, 1989, Balanced geological cross-sections: An essential technique in geological research and exploration: American Geophysical Union, Short course in geology, v. 6, 132 p.

Yeats, R. S., 1981, Quaternary flake tectonics of the California Transverse Ranges: Geology, v. 9, p. 16-20.

___ S. H. Khan, and M. Akhtar, 1984, Late Quaternary deformation of the Salt Range of Pakistan: GSA Bulletin, v. 95, p. 958-966.

___ and R. D. Lawrence, 1984, Tectonics of the Himalayan thrust belt in northern Pakistan: in B. U. Haq and J. D. Milliman, eds., Marine geology and oceanography of Arabian Sea and coastal Pakistan: New York, Van Nostrand Reinhold, p. 177-198.

___ and A. Hussain, 1987, Timing of structural events in the Himalayan foothills of northwestern Pakistan: GSA Bulletin, v. 89, p. 161-176.

___and R. J. Lillie., 1991, Contemporary tectonics of the Himalayan frontal fault system: folds, blind thrusts and the 1905 Kangra earthquake: Journal of Structural Geology, v. 13, p. 215-225.